Forecasting Research Division
Technical Report No. 73

Cyclogenesis:

Interpretation of Satellite and Radar Images for the Forecaster

by
Martin V. Young

November 1993

Forecasting Research

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Cyclogenesis: interpretation of satellite and radar images for the forecaster

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Preface

The main aim of the work in this Forecasting Research technical report was to produce a contribution on cyclogenesis for a new manual on interpreting satellite and radar images (Bader *et al.*, to be published). This report describes the original work carried out between 1985 and 1990. It was reviewed at a workshop in 1989 (Forbes, 1990).

Emphasis is placed on identifying and interpreting patterns on satellite and radar images and relating them to surface analyses as well as diagnostics from numerical models and conceptual airflow models. There are synoptic and mesoscale evolutions of six categories of cyclogenesis, illustrated by many case studies, along with guidelines for the operational forecaster. The cases are mainly over the eastern North Atlantic and western Europe but there are also some over the Pacific Ocean. Some new analysis techniques are introduced.

For the manual, the contents of the original work were re-ordered, the number of cases reduced and the illustrations produced professionally. Although the key points in the original work are the same as in the manual, several requests for a record of the original work, even if in a fairly rough form, have been received.

Many of the charts were produced by computer and the airflow models hand-drawn. The images, many of which are in colour, have been photocopied in black and white. Even so, the reader should be able to extract the key points. Many of the images are also in chapter 5 of the manual; originals of the others are available for inspection in Forecasting Research division.

Acknowledgement

The author wishes to thank Ruth Lilley for putting the material into a form suitable for reproduction.

Martin V. Young, November 1993.

5.0 INTRODUCTION

5.0.1 SOME BASIC DYNAMICAL CONSIDERATIONS

In this section some basic dynamical considerations relevant to cyclogenesis are introduced. These are discussed first in terms of quasi-geostrophic theory and then from the point of view of "potential vorticity". The concept of stable and unstable waves, (first introduced in Chapter 4) is applied and followed by examples of characteristic upper air patterns favouring cyclogenesis. These patterns shown will, later in this chapter, form the core of a framework for classifying cyclogenesis evolutions.

Stages in the development of a cyclone

Quasi-geostrophic viewpoint

Cyclone development at sea level occurs when and where an area of appreciable vorticity advection in the upper troposphere becomes superimposed upon a slowly moving or quasi-stationary front at sea level (Petterssen 1956)

5.0.1

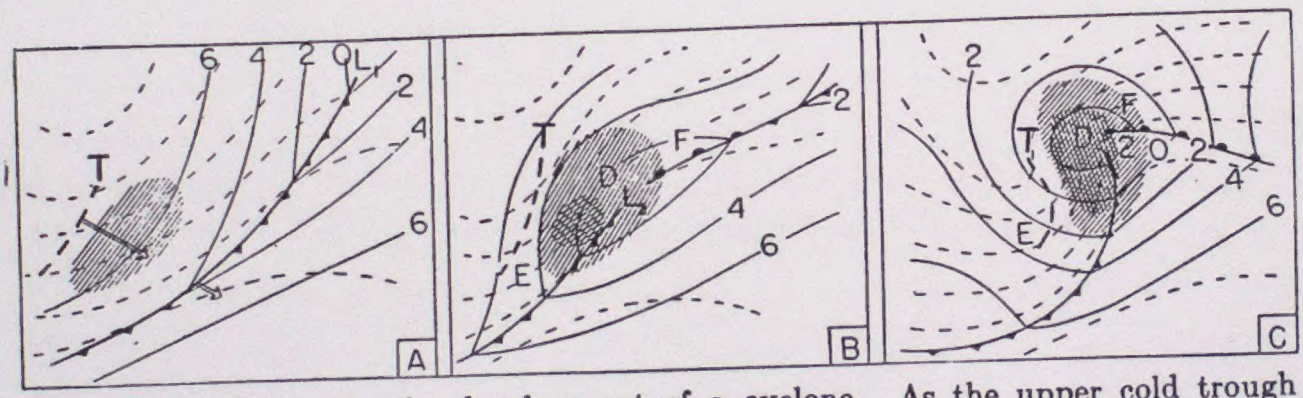

FIG. 5.0.1. Stages in the development of a cyclone. As the upper cold trough advances and the area of appreciable vorticity advection aloft (hatched area) spreads over the frontal zone, an imbalance is created which results in convergence at low levels. ~~Dines' compensation then shifts as shown in Fig. 14.4.2.~~ (Petterssen, 1986)

Stage A Pre-cyclogenesis

* Trailing cold front with cold advection in its rear and slight warm advection in the warm air
* Upper trough (bold dashed line) preceeded by an area of upper tropospheric positive vorticity advection, (PVA) say at 300mb, advances relative to the sea-level frontal zone

Stage B Incipient cyclogenesis

* Region D: vorticity advection predominates; thermal advection small.
  Region E: cold advection predominates; vorticity advection small.
  Region F: warm advection is relatively weak.
* Cyclonic development at D, anticyclonic development at E
* The system translates

Stage C Rapid deepening

* Warm advection dominates at F; cold advection dominates at E. In both regions, thermal advection is unopposed by vorticity advection

* Thermal structure has become such that cyclonic vorticity is produced in vicinity of F and destroyed in vicinity of E

* In region surrounding D, vorticity advection is unopposed by thermal advection and the cyclone will therefore continue to intensify

Potential vorticity (PV) viewpoint

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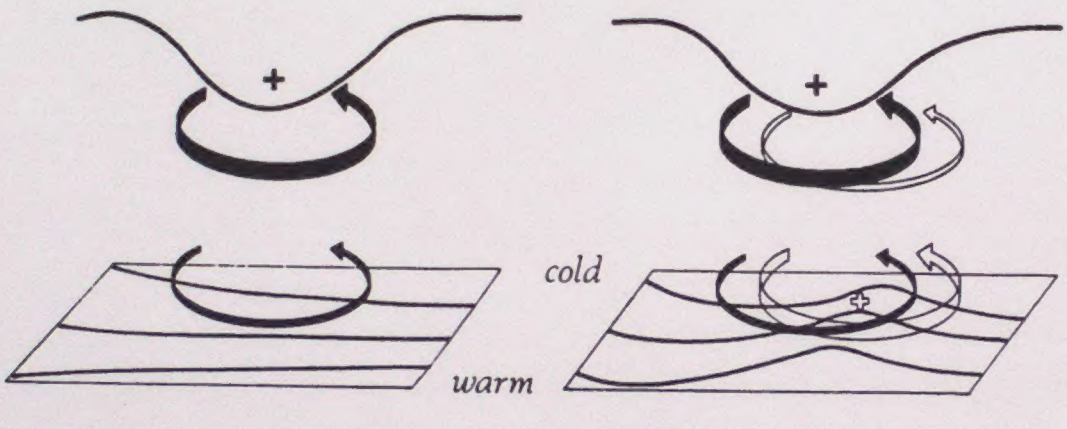


Figure 5.2. A schematic picture of cyclogenesis associated with the arrival of an upper air IPV anomaly over a low-level baroclinic region. In (a) the upper air cyclonic IPV anomaly, indicated by a solid plus sign and associated with the low tropopause shown, has just arrived over a region of significant low-level baroclinicity. The circulation induced by the anomaly is indicated by solid arrows, and potential temperature contours are shown on the ground. The low-level circulation is shown above the ground for clarity. The advection by this circulation leads to a warm temperature anomaly somewhat ahead of the upper IPV anomaly as indicated in (b), and marked with an open plus sign. This warm anomaly induces the cyclonic circulation indicated by the open arrows in (b). If the equatorward motion at upper levels advects high-PV polar lower-stratospheric air, and the poleward motion advects low-PV subtropical upper-tropospheric air, then the action of the upper-level circulation induced by the surface potential temperature anomaly will, in effect, reinforce the upper air IPV anomaly and slow down its eastward progression. (To this extent the situation is similar to the small-amplitude instability situation represented by Fig. and described in section .) (Hoskins et al, 1985)

Figure A: A cyclonic upper-air PV anomaly indicated by a solid plus sign (associated with a low tropopause in an upper trough) arrives over a pre-existing low-level baroclinic region. The circulation induced by the anomaly is indicated by solid arrows.

Figure B:

* Thermal advection by the induced low-level circulation will create a warm anomaly (indicated by an open plus sign) ahead of the upper PV anomaly

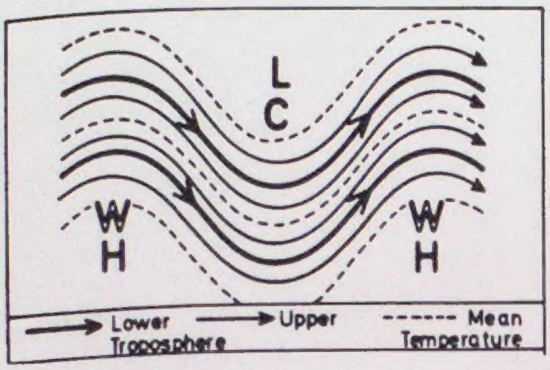
* The warm anomaly induces its own cyclonic circulation (indicated by open arrows) which will add to the low-level circulation induced from upper levels, sometimes leading to an intense low-level cyclone. This, in turn, reinforces the upper-level circulation.

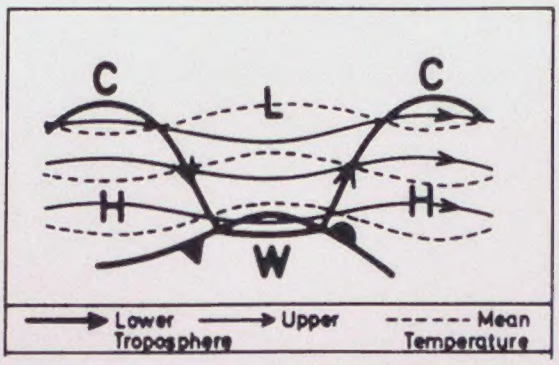
* Whilst the low-level anomaly remains ahead of the upper-level anomaly, there may be positive feedback to upper levels promoting mutual intensification of the two features.

Stable and unstable waves

The distinction between stable and unstable waves has already been introduced in Chapter 4. The cyclogenensis events to be discussed in this chapter will be examples of unstable waves.

Stable waves





* Fields of temperature (or thickness) and geopotential height must be in phase (left hand figure) or exhibit a phase difference of 180deg (right hand figure)

* Axes of troughs and ridges are upright

* The waves will translate with no change in amplitude

Unstable waves (i.e. cyclogenetic patterns)

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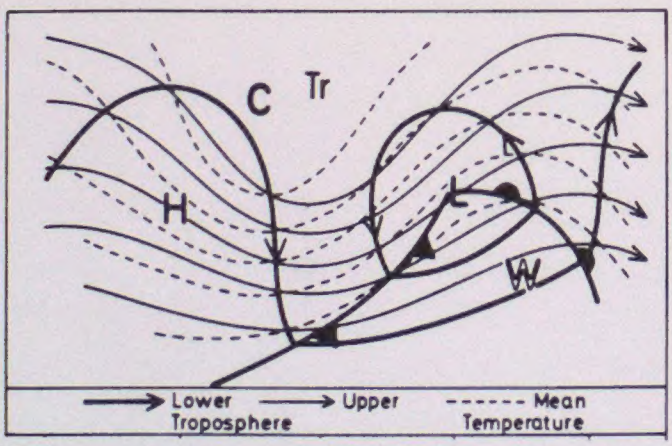
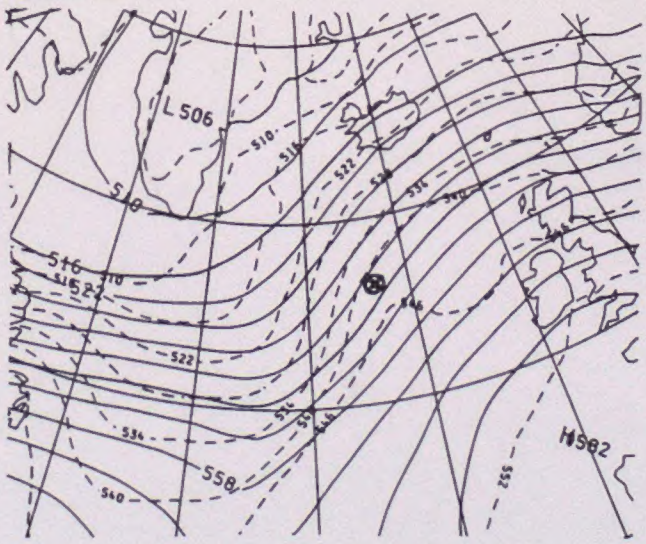




Super impose over image.

* Fields of temperature (or thickness) and geopotential height exhibit a 90deg phase difference, with the thermal wave lagging behind the wave in the geopotential field

* Axes of troughs and ridges tilt backwards

* The vorticity and thermal advection fields combine in such a way that they mutually reinforce one another, amplifying the trough-ridge pattern (and deepening the surface low).

* This positive feedback cycle of self-development terminates once the trough axis becomes upright i.e. the upper level low or trough moves directly above the surface low.

For further explanation see e.g. Kurz (1987), Haltiner and Martin (19..) or Petterssen (1956).

An example of an actual upper air pattern accompanying the development of an unstable wave is shown alongside. As in the schematic illustration, the thermal ridge, as well as the surface low, lie midway between the trough and the ridge in the contour pattern within a region of strong PVA. PVA is responsible for translating the pattern. However, the continued warm advection in the ridge and cold advection within the trough induced by the lower-level circulation acting upon the thermal fields will cause the trough/ridge system to amplify. The shape and simplicity of the cloud pattern reflects the simple wave-like pattern in the upper flow.

Some other factors affecting the intensity of cyclogenesis are as follows:

* INTENSITY OF THE BAROCLINIC ZONE

A more intense baroclinic zone favours stronger cyclogenesis

* STABILITY

Reduced static stability and the presence of deep convection near the depression centre favours more rapid cyclogenesis. Large values of slantwise available potential energy (Ref. Reed, Shutts) are thought to be an important pre-condition for explosive cyclones with a very intense core

* SENSIBLE/LATENT HEAT

Latent heat release accounts for a large proportion of the deepening rate (at least 40%) of many depressions (Ref. Reed)

Transfer of sensible heat and moisture from the sea surface into the boundary layer assists the above process

* UNDERLYING TOPOGRAPHY

Frictional effects: The deepening of a depression is significantly reduced due to increased surface drag as it moves from sea to land. (The reverse also appears to be true.) Even small land areas such as the British Isles can significantly reduce the deepening rate.

Mountains: A large range of mountains e.g. Alps can influence the evolution of the vorticity/thermal fields in such a way as to cause "lee cyclogenesis".

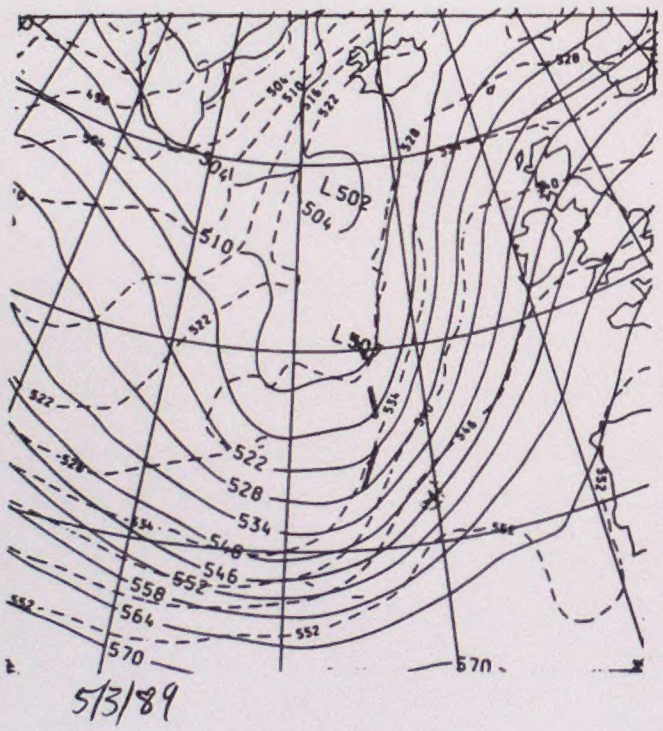
Coastal influence: Land/sea temperature differences (e.g. East coast U.S. Winter, N African coast springtime) establish a low level baroclinic zone which can provide a pre-conditioned environment for cyclogenesis given a suitable upper-level trigger.

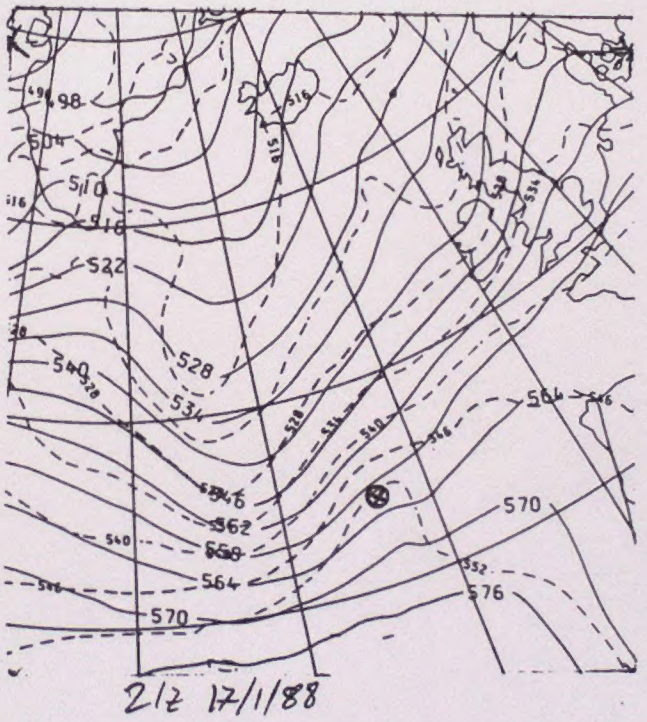
Cyclogenetic upper-air patterns

In most cases the synoptic-scale flow pattern is far more complex than that shown above, and involves interaction of waves of various wavelengths. This results in the wide variety of cloud shapes seen in the imagery during cyclogenesis. For quick reference, a number of the most common upper air scenarios preceeding cyclogenesis are shown, and are categorised according to the shape of the contour pattern at 500 or 300mb. These categories are exploited in sections 5.2 and 5.3 in conjunction with their associated cloud signatures.

Type 1 Meridional trough

Cyclogenesis often begins 5-10 degs of longitude forward of the base of a large amplitude upper trough. Sometimes (as in the left-hand figure) a short-wave (bold dashed line) can be found which moves into phase with the incipient surface low.





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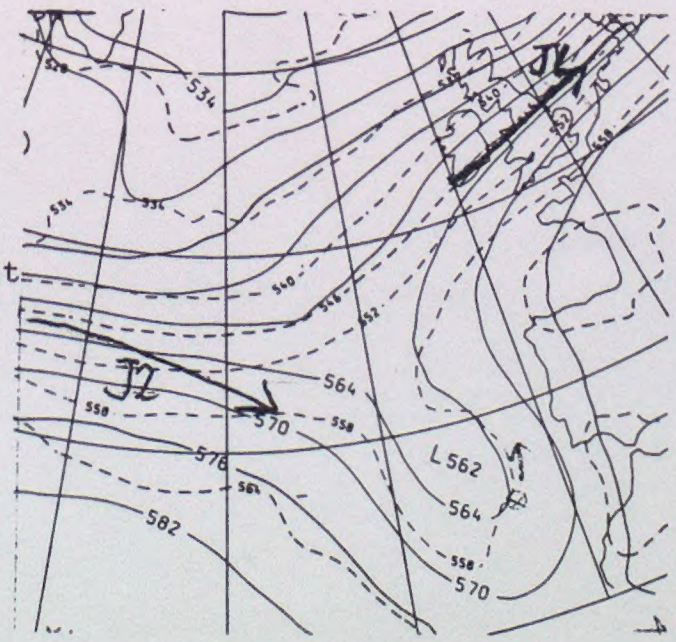
Type 2 Split flow

Pre-existing upper-level cut-off low. Upstream of the cut-off, the strong flow splits. The northern portion starts to cut across the upper trough whilst the southern portion lies to rear of the cut-off. The incipient surface low moves north on the forward side of the cut-off upper vortex, into the right entrance region of jet J1. Later on, rapid deepening occurs as left exit of J2 propagates across the upper trough.

north of cut-off low



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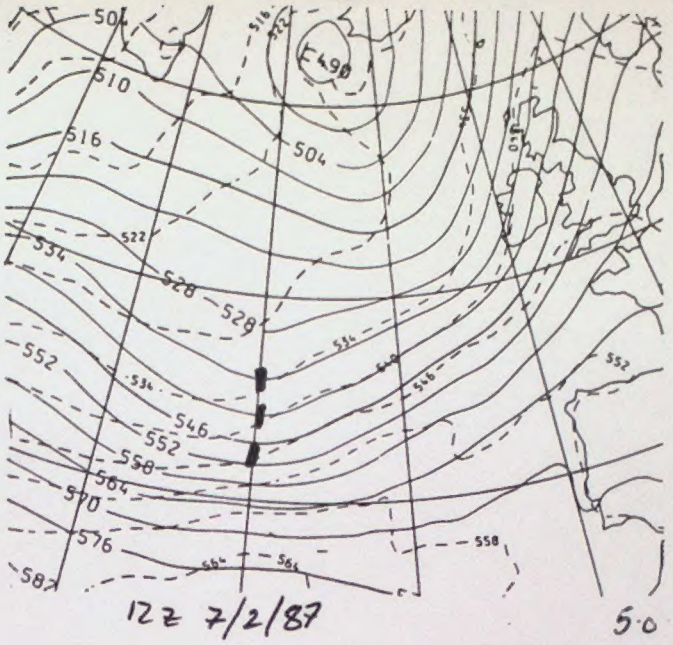
Type 3 Short-wave troughs

Cyclogenesis may occur ahead of a short-wave trough (dashed) moving through the region of strong upper flow around a very broad rounded upper trough. ~~These~~ Such short-waves may later interact with a forward frontal zone. left behind by a previous development



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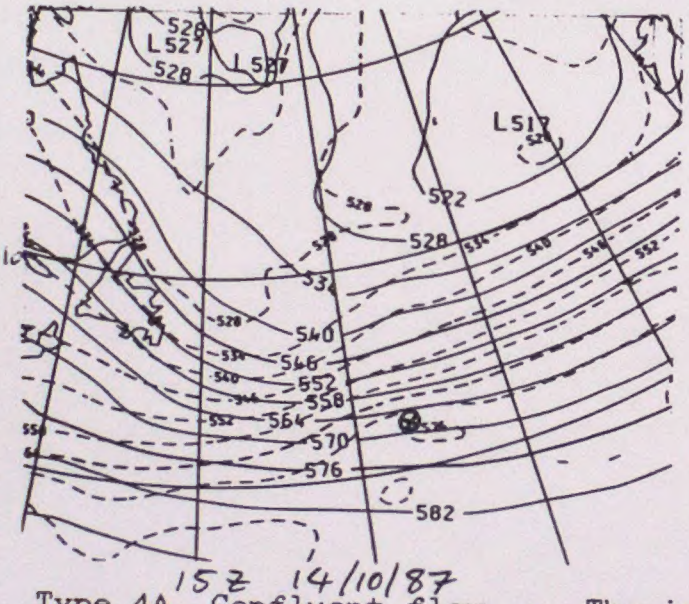
Type 4 Flat trough, zonal flow

Cyclogenesis often takes place within a region of initially almost zonal flow ahead of a flat trough.



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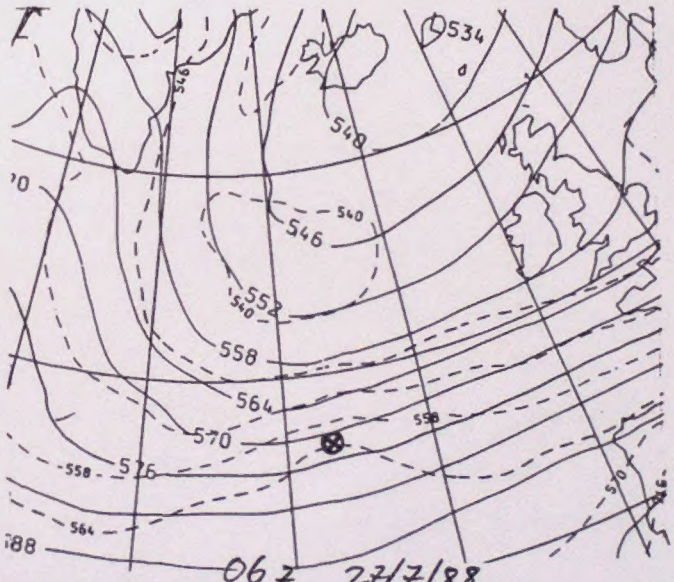

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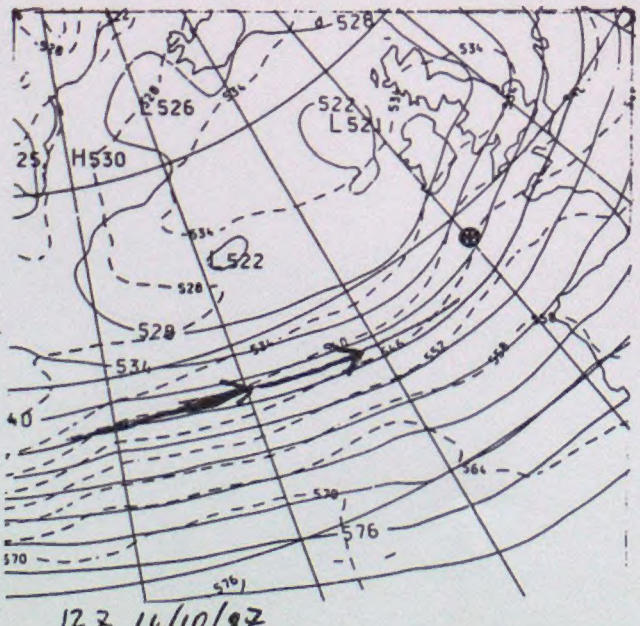
Type 4A Confluent flow - The incipient depression normally lies some 5-10 degs longitude east of an initially flat confluent trough.



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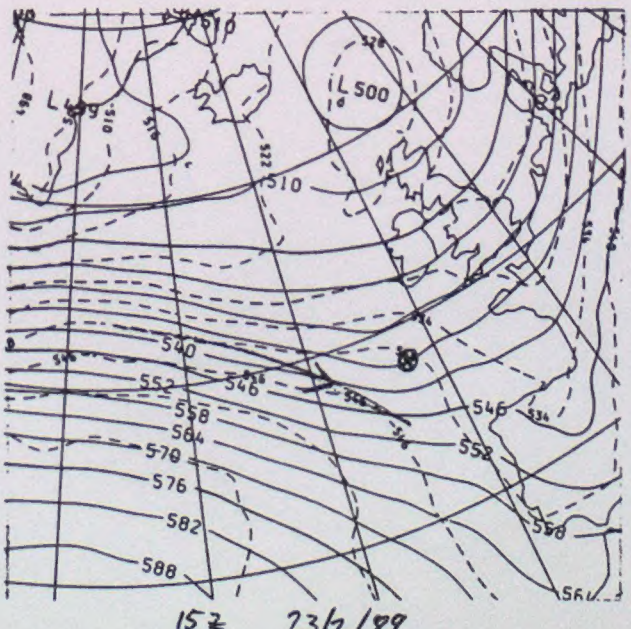

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Type 4B Diffluent flow - The developing depression usually lies immediately east (within 4 degs longitude) of an increasingly diffluent upper trough (at the left exit of a propagating jet).

5.0.3 FRONTAL EVOLUTIONS

Traditional Norwegian frontal models have been a proven powerful tool in analysing and forecasting evolution of mid latitude cyclones. However, rigid adherance to this model is in some cases misleading (or an over-simplification) in terms of its representation of evolving thermal fields as well as cloud and rainfall distribution.

Common variations to the traditional model are shown in this section with particular attention being focused on the concept of "back-bent warm front", "seclusion" and "instant occlusion".

Bent-back warm front and seclusion

Analysis of thermal fields e.g. 850 θ_w and 1000/500mb thickness suggests that in many cases a true occlusion process does not occur, notably in the vicinity of rapidly deepening depressions.

A typical sequence of events is illustrated below.

(a) **Incipient Wave** Prior to rapid deepening, a wave forms on a region of intense thermal gradient.

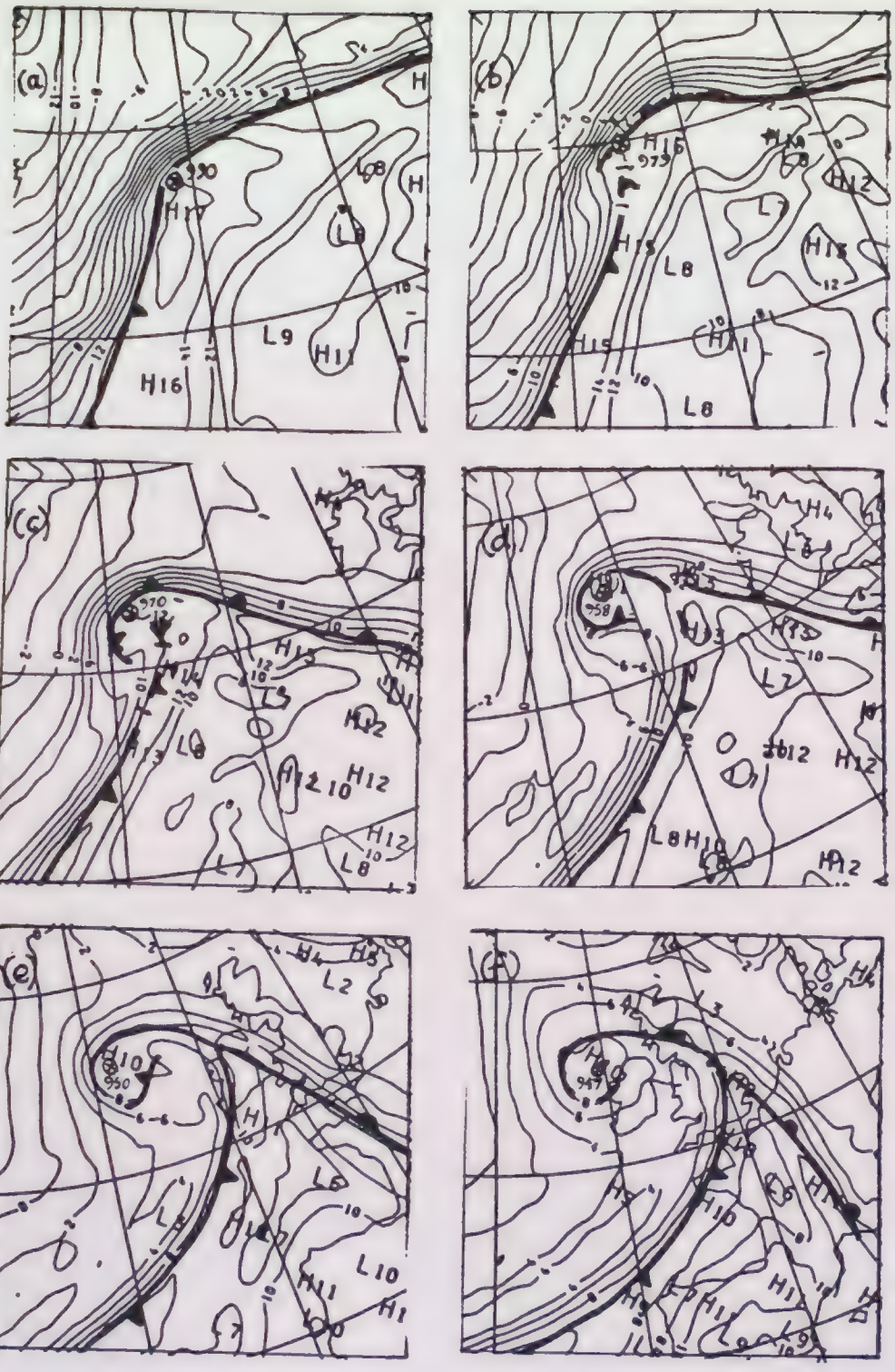
(b) **Frontal Fracture** The region of strong thermal gradient weakens (fractures) immediately to the rear of the depression i.e. cold frontolysis. This leaves the strongest thermal gradients concentrated ahead of the warm front and along the cold front remote from the depression centre.

(c) **Bent-back warm front** The region of strong thermal gradient ahead of the warm front moves around the rear of the depression forming a bent-back warm front.

(d) **Warm core seclusion** A narrow filament of low-level warm air becomes isolated over the depression centre ("seclusion") during rapid deepening whilst the region of strong thermal gradient continues to wrap around the depression.

(e), (f) During further evolution the warm air aloft remains isolated over the depression. As the system matures, a tongue of air from the warm sector is drawn around the vortex and takes on an appearance more akin to the traditional occlusion.

The processes described above are illustrated schematically at the bottom of the page: the left hand, centre and right hand figures corresponding to figs (a), (c) and (f) respectively. (The inset shows the corresponding traditional anaysis in which the occlusion symbol is introduced even though a true occlusion process has not taken place.)



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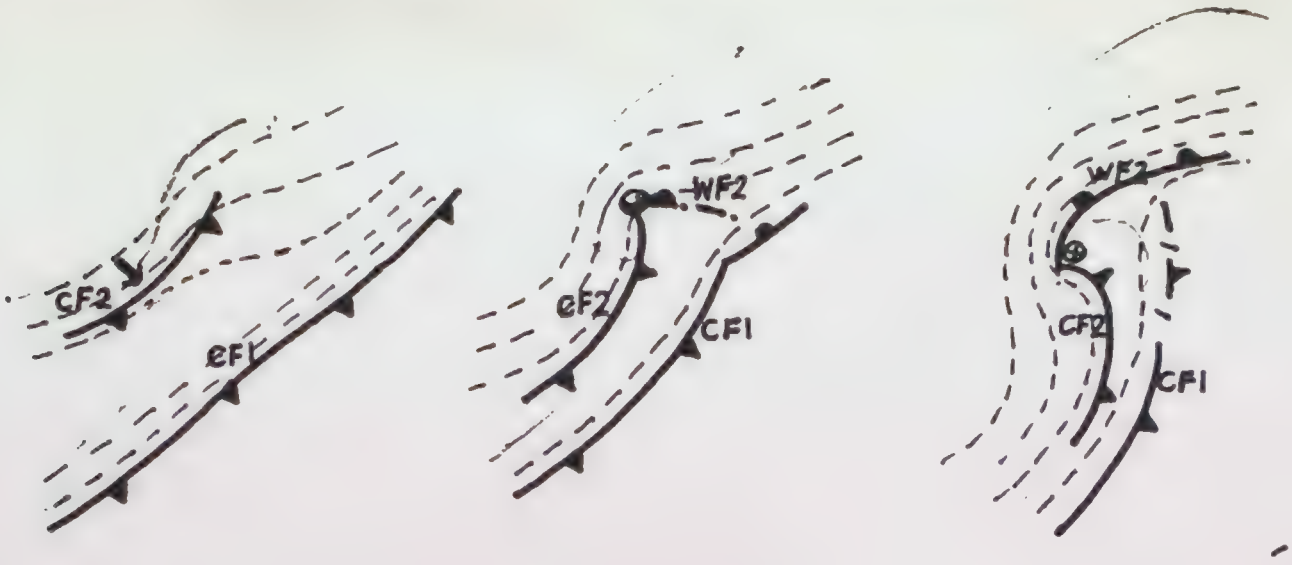
5.0.15

Interaction of two frontal zones



S.O. 16

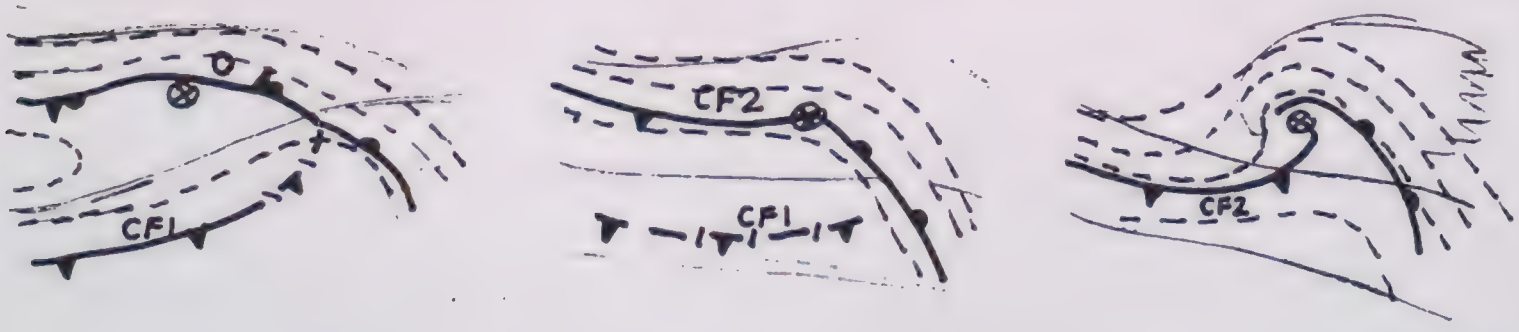
Left hand figure: This evolution usually involves the approach of a secondary baroclinic zone associated with CF2 towards older front CF1.

Centre figure: When cyclogenesis occurs on the cold side of CF1, a new warm frontal zone WF2 develops ahead of the deepening low. A minor wave is often induced on CF1.

Right hand figure: Forward cold front CF1 progressively frontolyses. CF2 sweeps around the depression centre, sometimes secluding a small region of warm air over the depression centre. A single warm frontal zone now extends east from the centre. Note how the analysis has evolved into a similar pattern to Fig. ??

This cyclogenesis evolution is often referred to as the "instant occlusion" since on imagery, the cloudbands associated with the two frontal zones appear to merge culminating in a system which, on imagery, appears like a mature occluded depression, even though no occlusion process has occurred.

Rejuvenation of old occluded depression



S.O. 17

Left hand figure: After a depression has occluded, a residual strong thermal gradient can be left lying immediately poleward of occlusion O, whilst cold front CF1 is poorly defined thermally.

Centre and right hand figures: Approach of an upper level short-wave from upstream will sometimes trigger renewed cyclogenesis within the region of strong thermal gradient associated with O. It will then be appropriate to redefine O as a simple warm front/cold front system whilst the historical cold front CF1 ceases to be identifiable.

5.0.4 FRONTOGENESIS AND CYCLOGENESIS: RELATIONSHIP BETWEEN AGEOSTROPHIC CIRCULATIONS AND CLOUD PATTERNS

Frontogenetic stage (Figs (a,b,c))

* The open wave lies beneath the right entrance region of a jet J (Fig. (a)).

* Frontogenesis is taking place at this stage and is accompanied by a direct circulation cell C1 seen in the cross section along X1-X2 (Fig. (b). This circulation gives rise to a classical rearward-sloping frontal archetype.

* In terms of conveyor belts, Fig. (c) we have an ascending warm conveyor belt W1 accompanying frontal cloudband F. To the rear of F we have descending cold air which undercuts W1 behind the surface cold front.

Cyclogenetic stage (Figs (d,e,f))

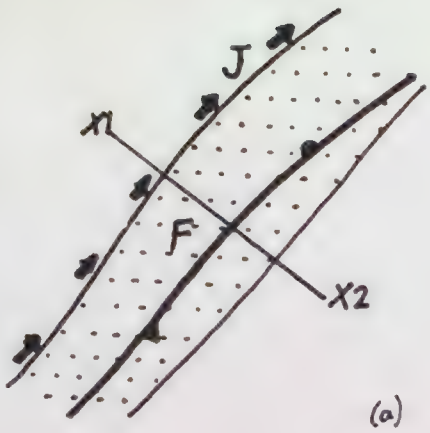
Frontal zone and the associated jet J have now "fractured" in the manner described in section 5.1.3. The deepening depression is now situated between the left exit of J1 and the right entrance of J2 (Fig. (d)).

Frontogenesis occurs along the warm front and its "bent-back" extension around the rear of the depression. The cross-section along Y1-Y2 (Fig. (e)) shows the corresponding new direct circulation cell C2 in this frontogenetic region, located at P. This direct circulation corresponds to the right entrance of J2. The ascending branch of C2 is simultaneously reinforced by the ascending branch of new indirect circulation cell C3 induced at the left exit of J1. (The sense of the circulation around the original frontal zone has effectively been reversed in this region, consistent with frontoloysis which is taking place). Further downstream away from the depression centre a section along Z1-Z2, across the warm front, would show a direct circulation, similar to Fig. (b).

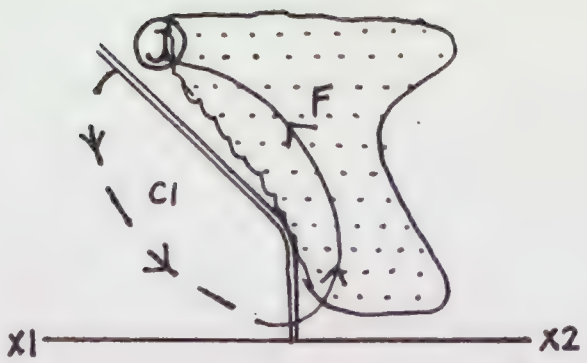
The ageostrophic circulations of J1 and J2 are therefore coupled resulting in development of new strong slantwise ascending motion above P - manifested by the formation of a secondary warm conveyor belt W2 (Fig. (f)), emerging from beneath W1, and the simultaneous growth of layered cloud C on the cold side of F. This signature is characteristic of the deepening phase of most depressions.

The weakening frontal zone to the east of the depression is now confined to middle and upper levels (Fig. (e)), and the warm air in W1 is elevated well above the surface in this region.

The tongue of dry air separating C and F consists of recently subsided mid and upper level air which has arrived from upstream (open arrows on Fig. (f)) beneath and to the cold side of J1. Near the surface, cold air (dashed line) - a cold conveyor belt - originating ahead of the warm front and moistened by heavy precipitation beneath C, moves around the rear of the depression and arrives alongside dry cold air originating upstream of the depression.



(a)



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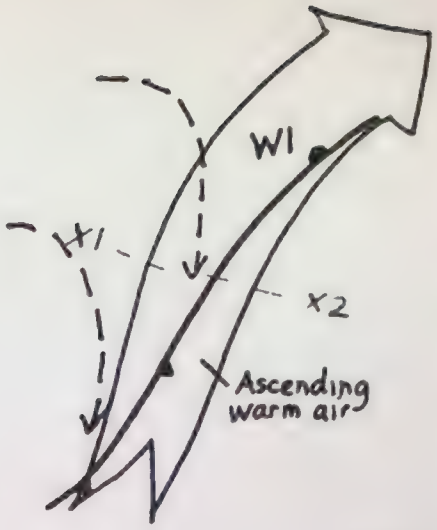

(c)

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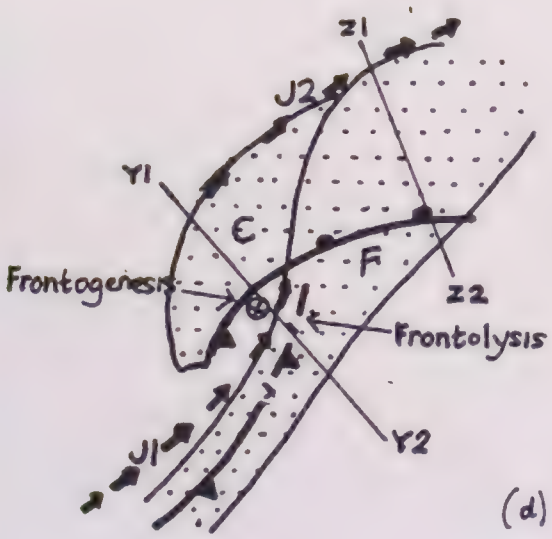
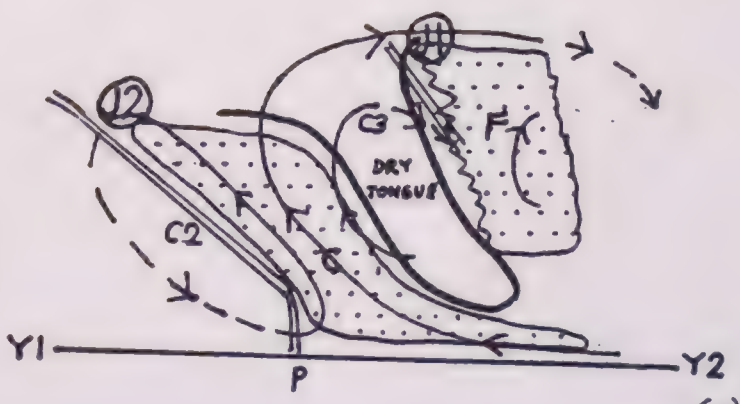
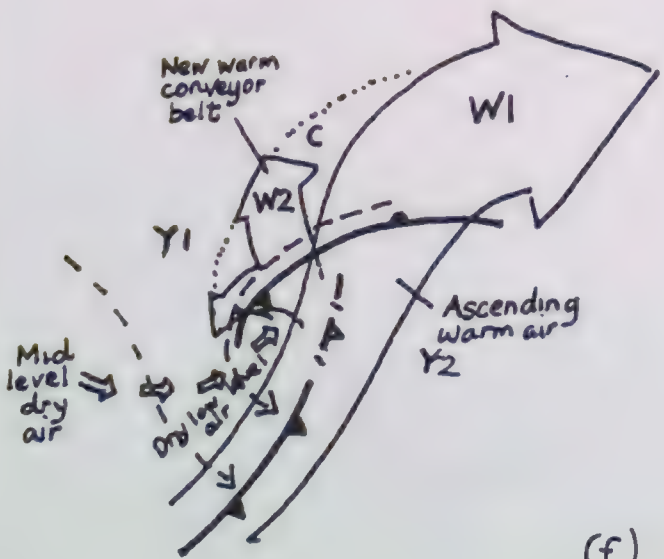


(d)



(e)



(f)

Cloud

Frontal zone

⊗ Depression centre

Ⓙ Jet axis

11

5.1 CLOUD SIGNATURES AT VARIOUS STAGES OF CYCLOGENESIS

5.1.1 CLUES FROM SATELLITE IMAGES

Shapes of cloud systems and their subsequent evolution can provide the forecaster with very helfpul clues on identifying

* The **possibility of cyclogenesis at an early stage**

* **Where** cyclogenesis will occur

* **Whether explosive deepening is likely**, with a warning of up to 24 hours of very strong surface winds

* The **most probable location of the depression centre and strongest winds**, especially later in a depression's life-cycle

* The **likely track of a depression**, mainly from extrapolating cloud signatures between successive images

* The **most likely distribution of precipitation** and its intensity

(See cautionary note p~~XXX~~ 12)

The examples in the next section (5.2) will, by exploiting the upper air pattern, help the forecaster to identify the type of cyclogenesis in real time and thereby, predict the probable evolution of the cloud shapes.

5.1.2 CLOUD CONFIGURATIONS EARLY IN CYCLOGENESIS

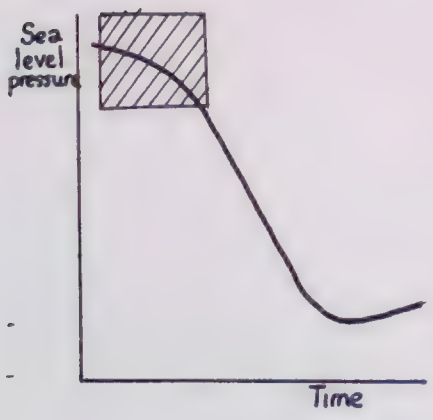
Clues of imminent cyclogenesis come chiefly from patterns associated with

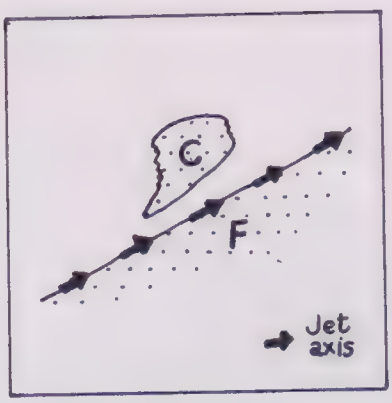
* **Bands of frontal cloud**, F, along or to the ~~south~~ warm side of the main jet

* **Cumuliform or stratiform cloud**, C, on the cold side of the jet

Fig

Stage I





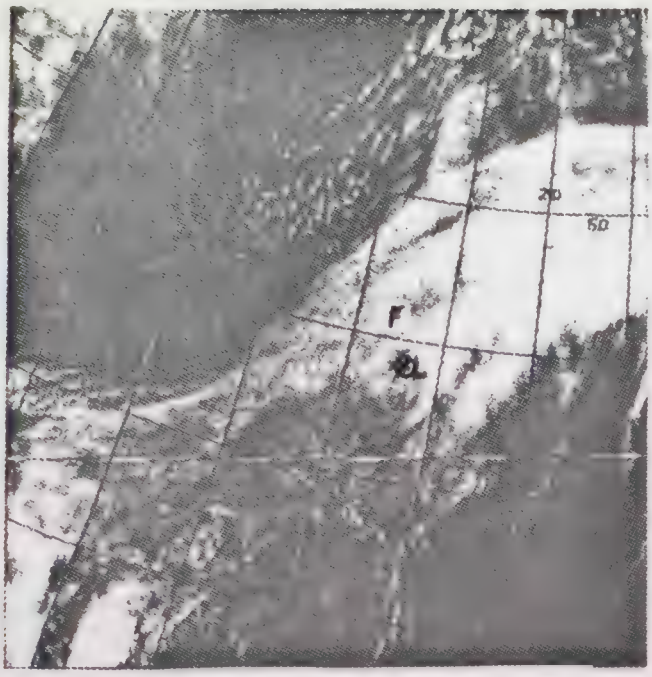
15Z 7/11/89

5.1

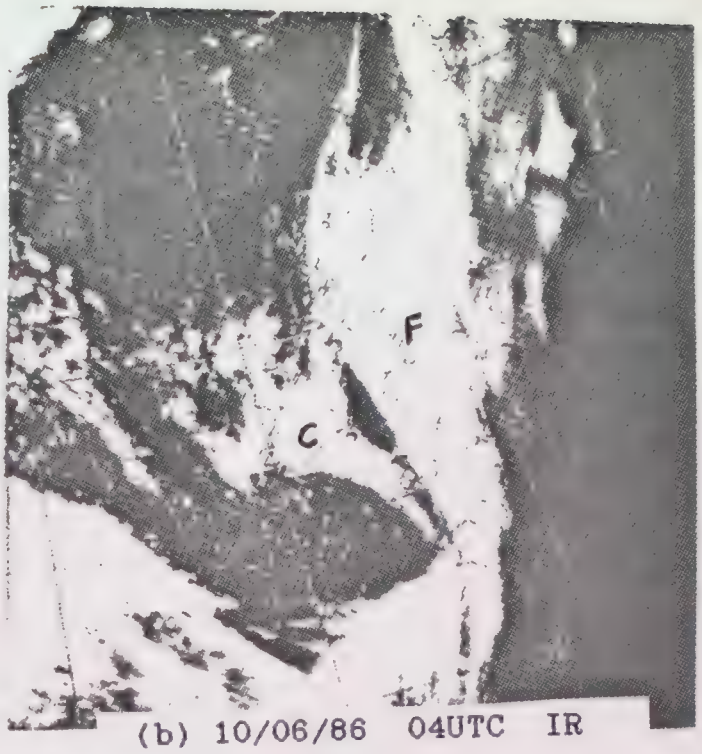
One or both of F and C may be present in any given event. Both features vary considerably in size and shape from case to case.

It is normally too early at this stage to establish the exact position of the surface low centre from the images - it is also quite possible that there may not yet be a well-defined centre.

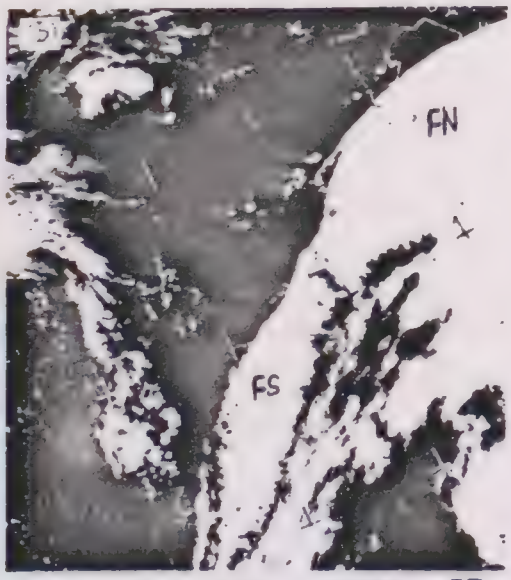
CHARACTERISTIC SHAPES OF F



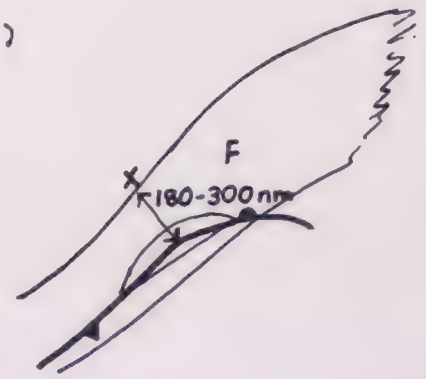
(a) 17/01/88 20UTC IR



(b) 10/06/86 04UTC IR



(c) 26/11/83 10UTC IR



p. 3.

SURFACE LOW - several minor centres likely within elongated trough; the "centre of gravity" of the low lies beneath F adjacent to the inflection point X of the S-shaped rear edge, some 180-300nm in from the edge.

* Note: If F is narrow i.e. < 240nm wide, place low in middle of cloud band eg. (b)

Clues from F for further deepening

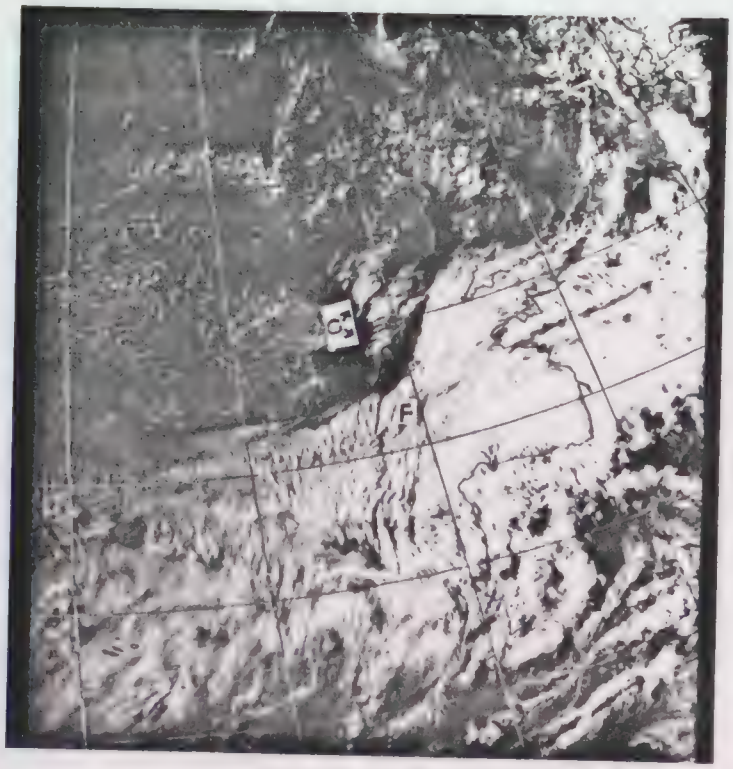
* develops an increasingly S-shaped rear edge as in (a) and (b)
* broadens and cools, often close to convective comma C as in (b)
* narrows and dissipates upstream as in (a)
* may break up into more than one distinct (leaf-shaped) enhanced area of cold tops e.g. areas FN and FS in Fig. (c)

For further discussion see pXXX Types 1, 3B

→ Sections 5.3.1, 5.3.3B

CHARACTERISTIC SHAPES OF C

(i) Convective clusters



5.1.4 (a) 14/10/87 09UTC VIS

(b) 05/01/88 04UTC IR

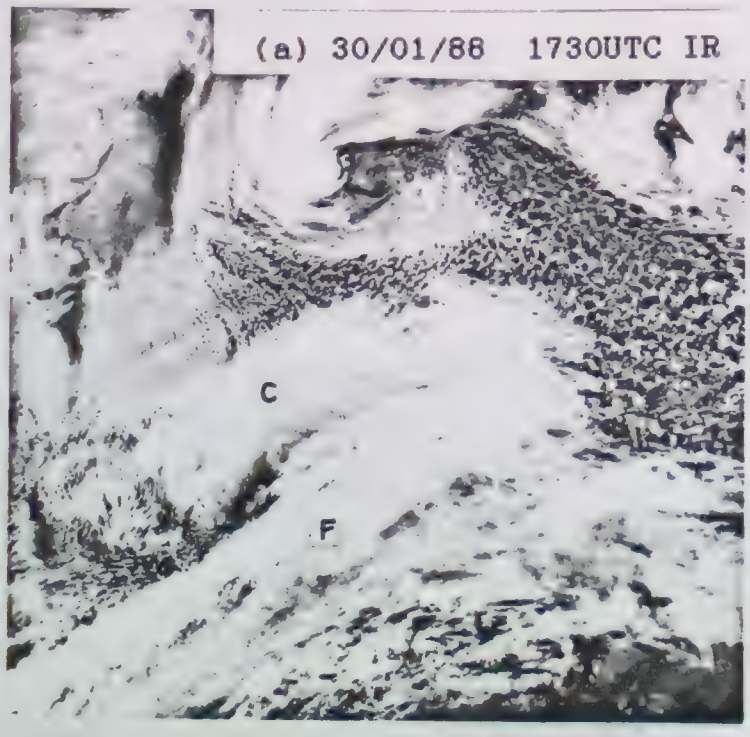
(c) 10/06/86 04UTC IR see previous page

Clues from C for further deepening

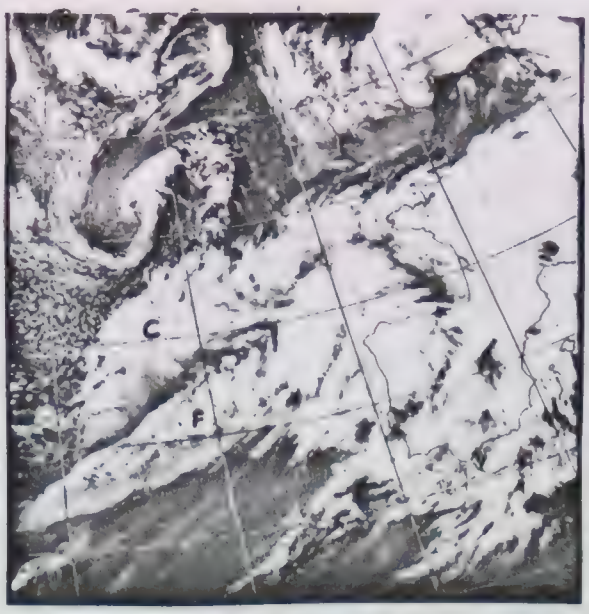
* Clumps of deep convection, C, continue to grow on cold side of F as in (a)

* C becomes organised into a comma-shape as in (b), usually expanding, with anvil cirrus moving downwind. C may subsequently merge with F

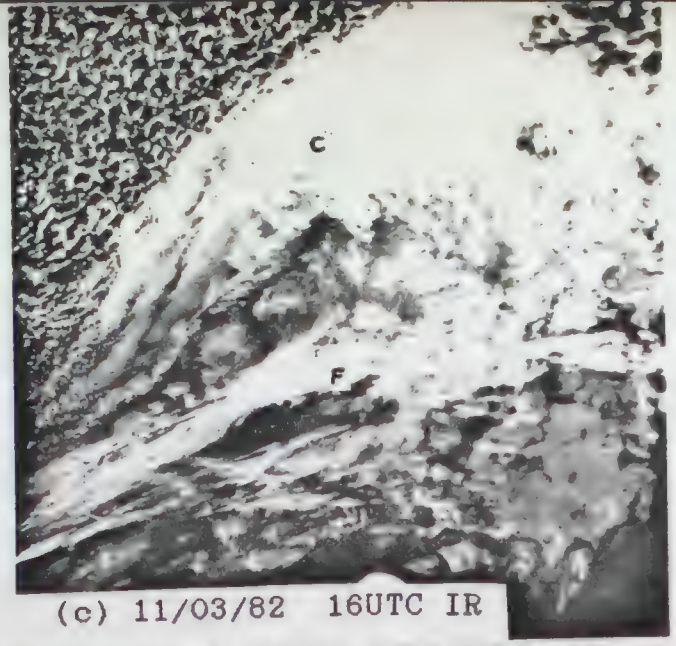
(ii) Layered cloud



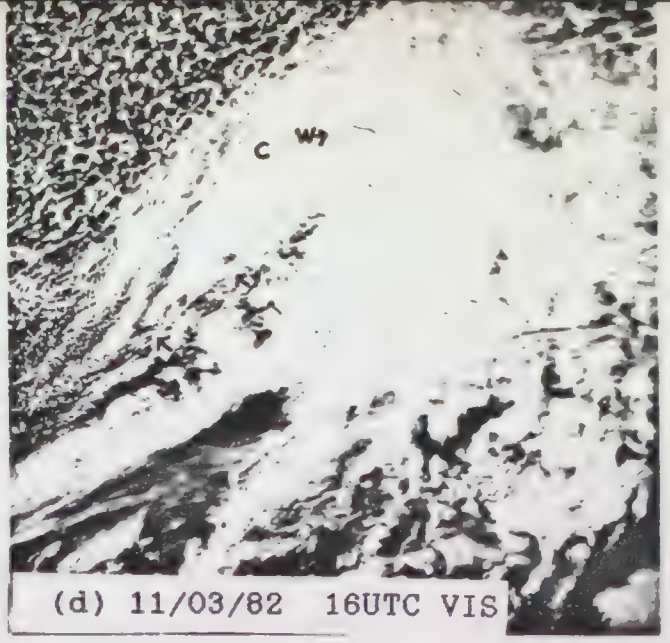
(a) 30/01/88 1730UTC IR



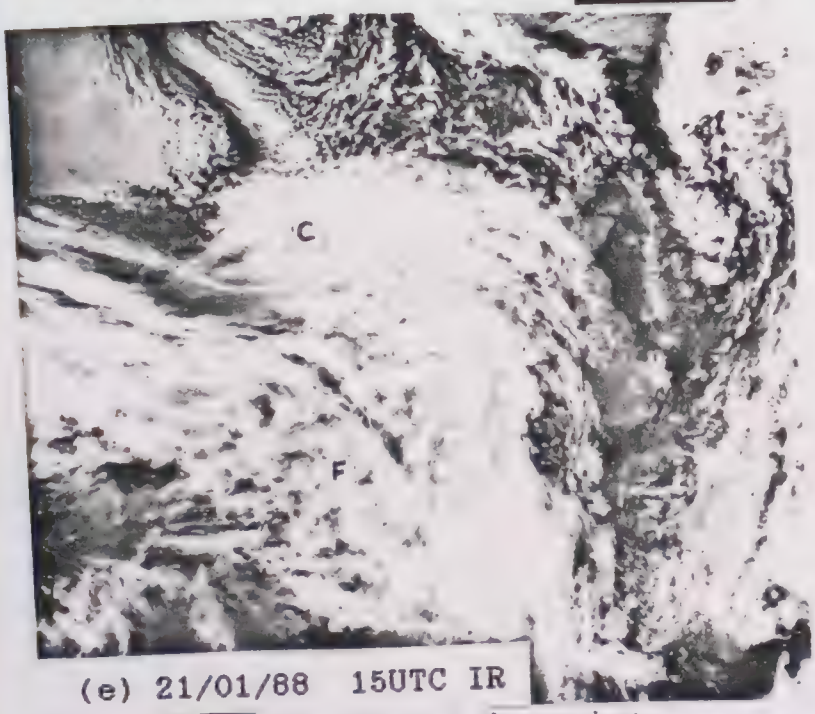
5.1.5 (b) 15/10/87 0430UTC IR



(c) 11/03/82 16UTC IR



(d) 11/03/82 16UTC VIS



(e) 21/01/88 15UTC IR

5.1.6

SURFACE LOW - elongated and sometimes complex; lies beneath warm cloud tops on inside rear portion of C, or beneath the dry (cloud-free) wedge if one is present

Clues for further deepening

(1) Broad, elongated area of layered cloud, C, immediately poleward of F, with progressively colder tops towards its poleward edge, which is at least slightly convex.

(2) Narrow ~~wedge~~ region, free of cold cloud tops between C and F - the "dry wedge"

(3) Open cellular cumuliform cloud pattern extends beneath poleward edge of C

If (1) and (2) are both particularly well-defined as in Figs (a)-(d), the pattern is called a "CLOUD HEAD" (Bottger et al. 1975).

*** A well-defined cloud head is a reliable precursor of explosive deepening (usually well in excess of the "bomb" criterion of 24mb per day), with hurricane-force surface winds some 18-24 hours after the signature first appears**

(e) is similar to a cloud head, but the cloud-free wedge is less prominent and the associated low will probably not deepen as rapidly as those in (a)-(d)

Note:

* If rope-like cloud structure lies along inside edge of C (arrowed in Fig. (d)), this marks the sharp surface cold front

* If the convection in the immediate vicinity of C appears undisturbed, any cyclonic circulation is either small or non-existent as yet

For further discussion see page ~~Appendix~~ 35 Section 5.3.4A

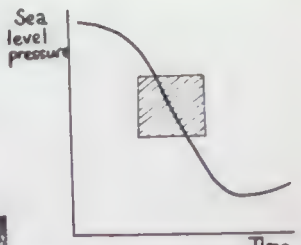
5.1.3 CLOUD CONFIGURATIONS WHEN CYCLOGENESIS IS UNDERWAY (STAGE II)

This section presents clues from the imagery for

* Identifying depressions which already possess a surface circulation and are continuing to deepen

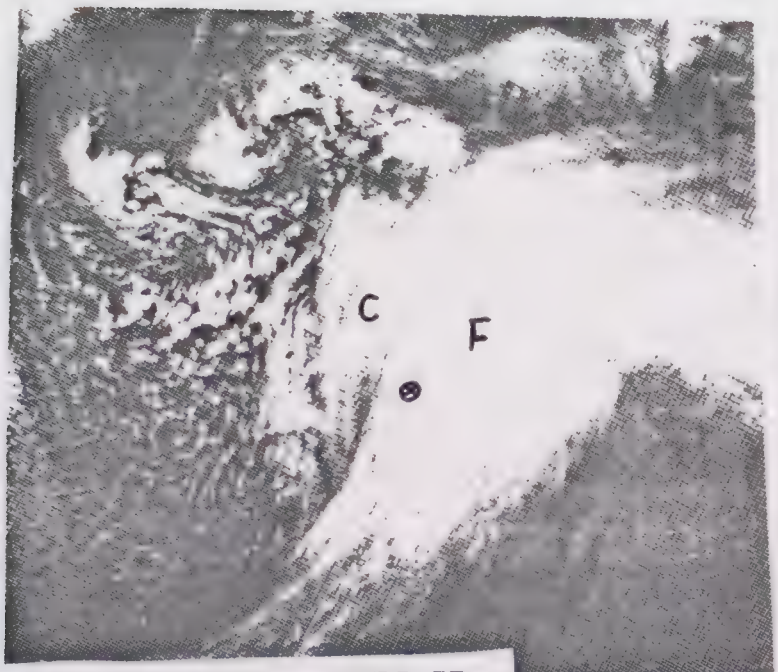
* Rules for locating the surface low centre.

5.1.7

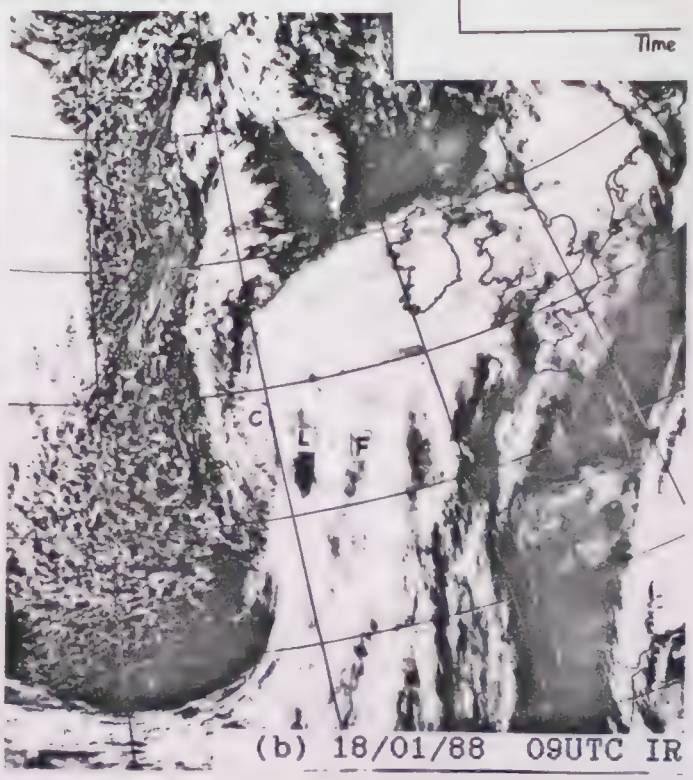


5.1.8

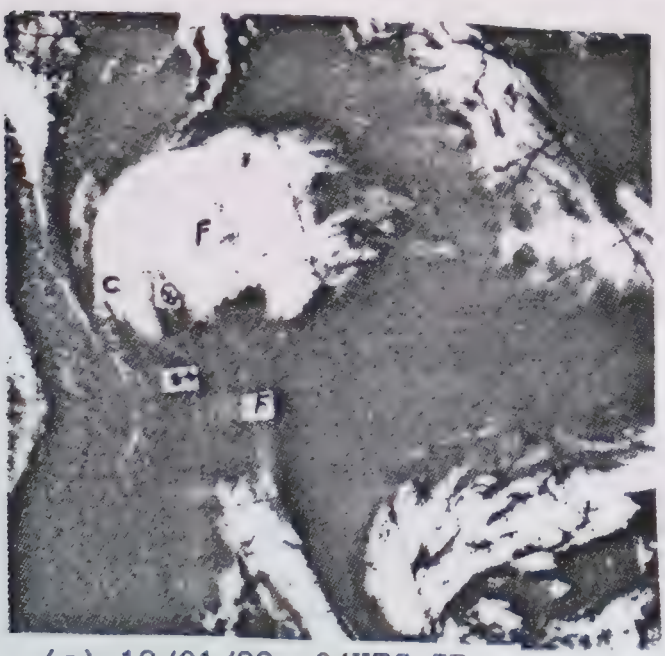
CHARACTERISTIC SHAPES EMANATING FROM F



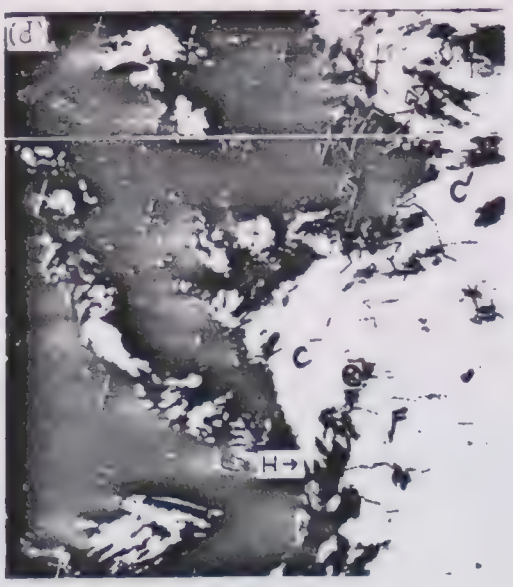
(a) 21/12/88 13UTC IR



(b) 18/01/88 09UTC IR



(c) 19/01/88 04UTC IR



(d) 26/11/83 16UTC IR

Clues for further deepening

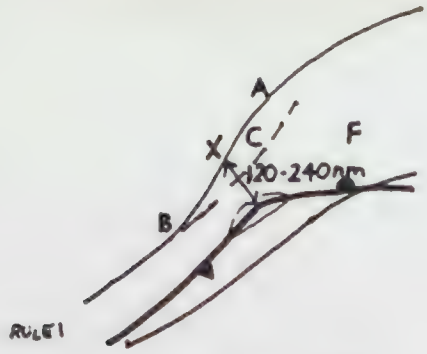
* Poleward edge of F becomes increasingly S-shaped and strongly convex downwind as in (a) and (b)

* Area of mid or upper level cloud (leaf) C, emerges from beneath F. Early stages of this process depicted in (a) and (b), whilst in (c), C has entirely emerged, revealing warm tops on its inner edge.

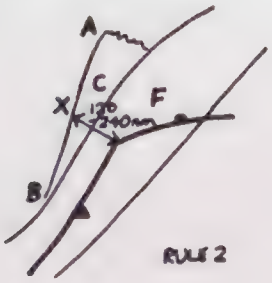
* Cirrus dissipates upwind of C as in (b) and (c)

SURFACE LOW

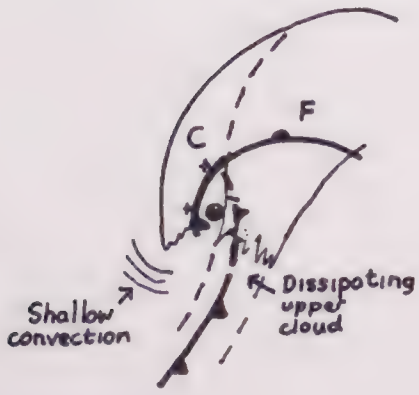
5.1.9.



RULE 1



RULE 2



RULE 1 Consider the rear edge of the cloud as an S-shape. Locate X, the inflection point of the S. Draw a line from X into the cloudband at 90deg to the surge line. The centre will lie 120-240nm in from the rear edge. * e.g. (b)

RULE 2 If it is not easy to locate the infection point (e.g. if AB is a straight edge), then find the point X midway between the apex A of the extension and the point B where it tucks beneath F. The centre lies 120-240nm in from the rear edge along a line projected from X at 90deg to the surge. e.g. (a)

RULE 3 Look for substantial thinning of the upper cloud shield immediately upwind of the low.

* Note: If F is narrow i.e. < 240nm wide, place low in middle of cloud band

As C continues to emerge from beneath F, the depression centre remains at the same distance from the rear edge of C.

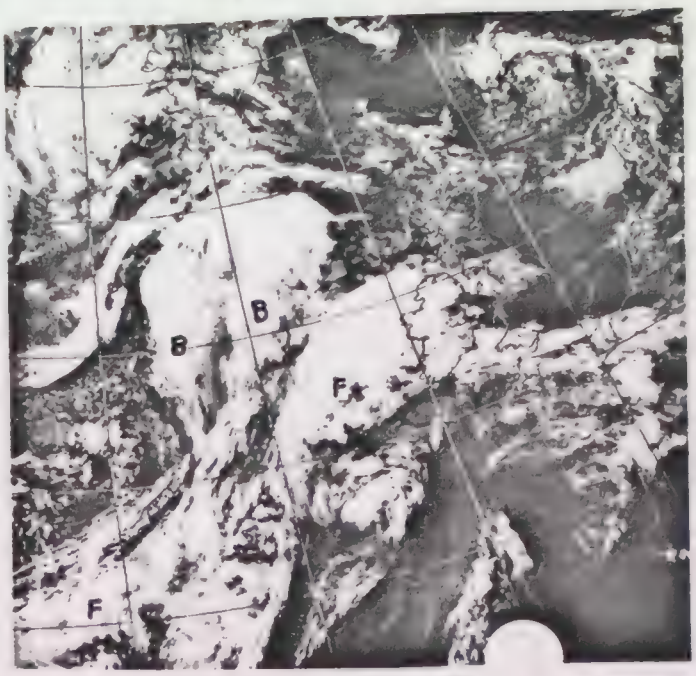
RULE 4 When C has become well separated from F, revealing warm cloud tops (usually within 10deg of surface temperature) along its inner edge, a single low centre lies in the new dry slot, beneath the warmest cloud tops on the inside of C, towards its upstream end. e.g. (c), (d)

For further discussion see Type 1

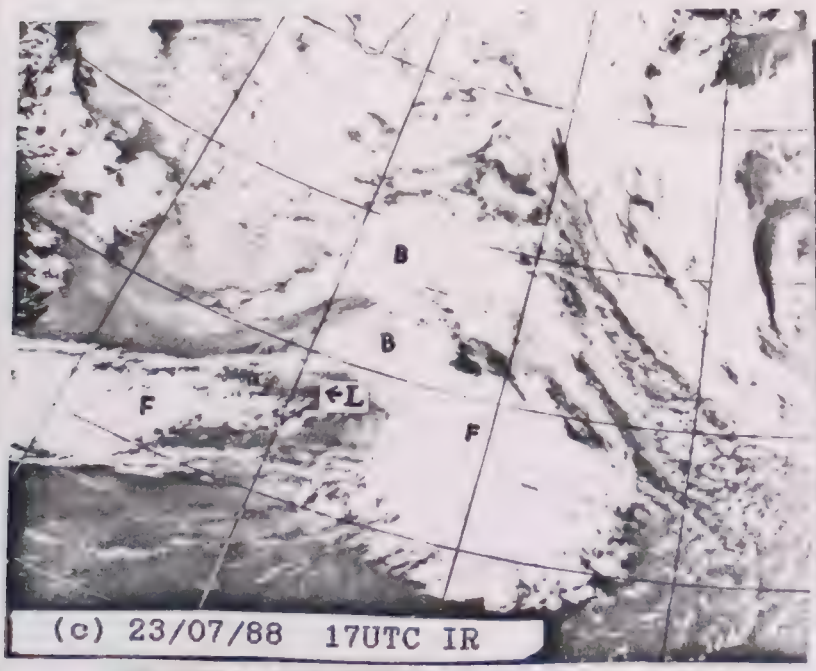
CHARACTERISTIC SHAPES OF C ALONE OR C INTERACTING WITH F

(i) More than one cloud area comprising C, or C largely convective

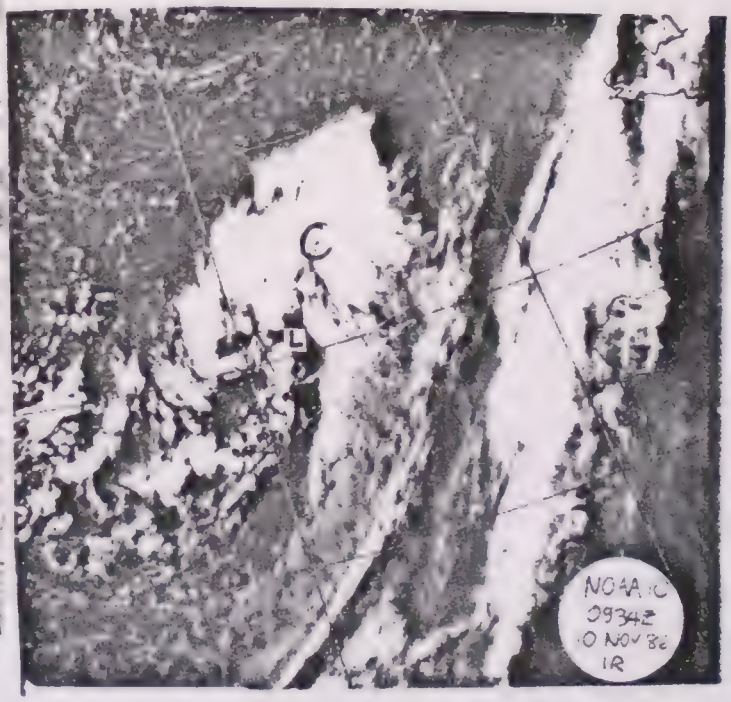
(a) 14/10/87 15UTC IR



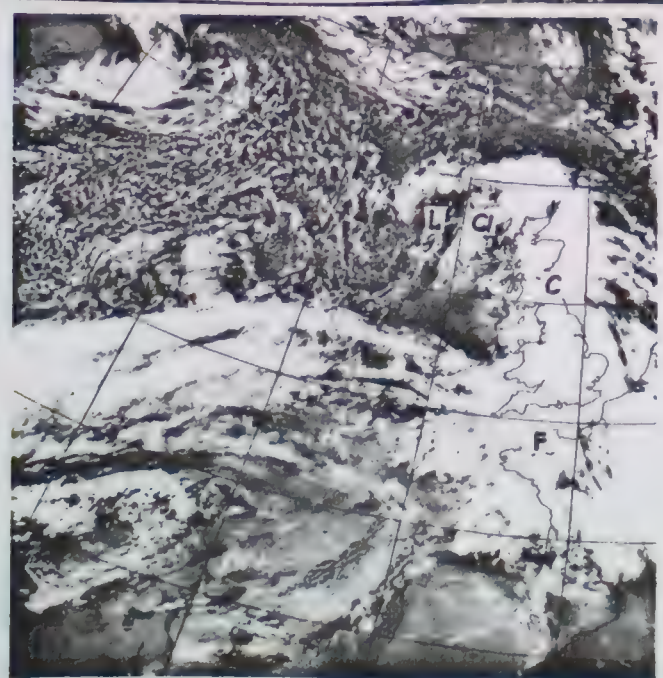
(b) 11/09/87 09UTC IR



(c) 23/07/88 17UTC IR



(d) 10/11/86 0930UTC IR



(e) 17/12/86 1530UTC IR

Clues for further deepening

* Extending area of cloud poleward of F, often in form of convective cloud with considerable cirriform outflow as in (a)

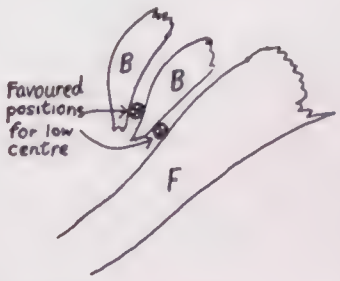
* Separate areas of layered cloud, B, ("mini-leaves"), often aligned at a small angle to F, as in (b) and (c)

* Well-defined comma-shaped cloudmass with embedded convection as in (d)

5.1.11

SURFACE LOW

* At the rear edge of C near the most rapidly growing convective elements. These will often "radiate" from the position of the low centre e.g. (a) and (d)



* Beneath the warmest cloud tops along the inside edge of one of the mini-leaves, B e.g. (b) and (c)

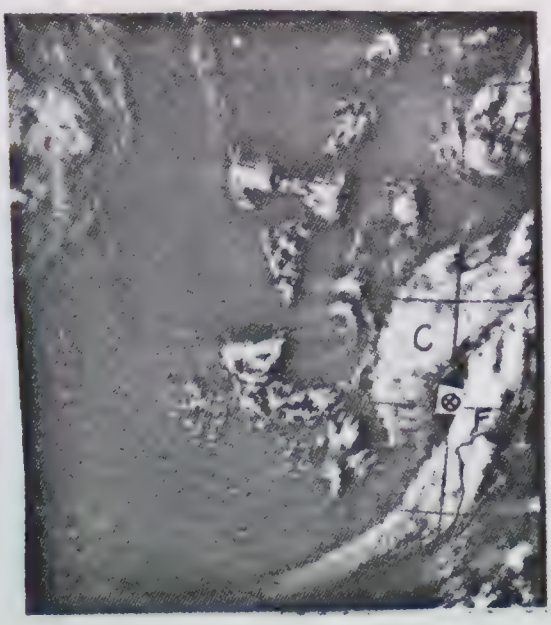
* Within a small comma-shaped cloud area C1 situated at the rear of C e.g. (e)

For further discussion see Types 3A and 4B

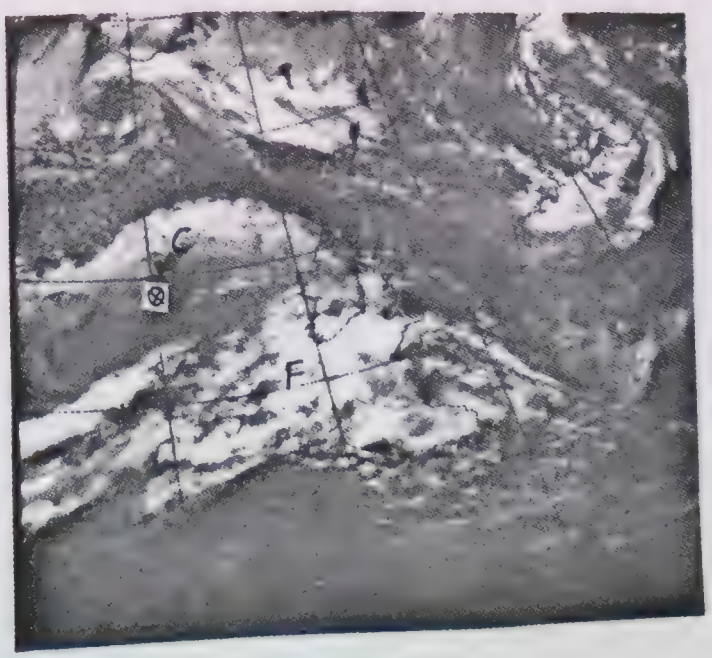
5.1.12

single cloud area;

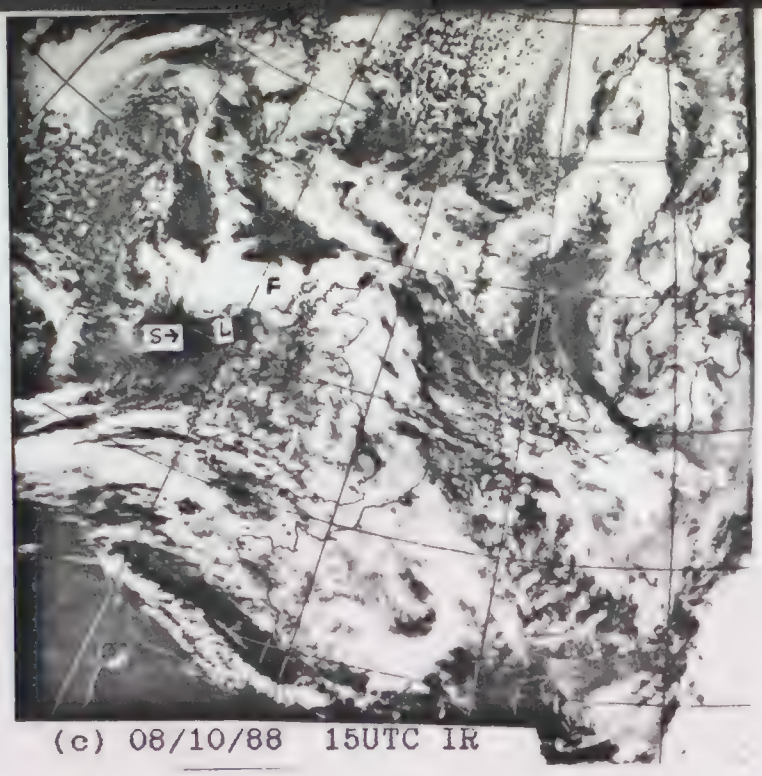
(ii) C_L predominantly layered



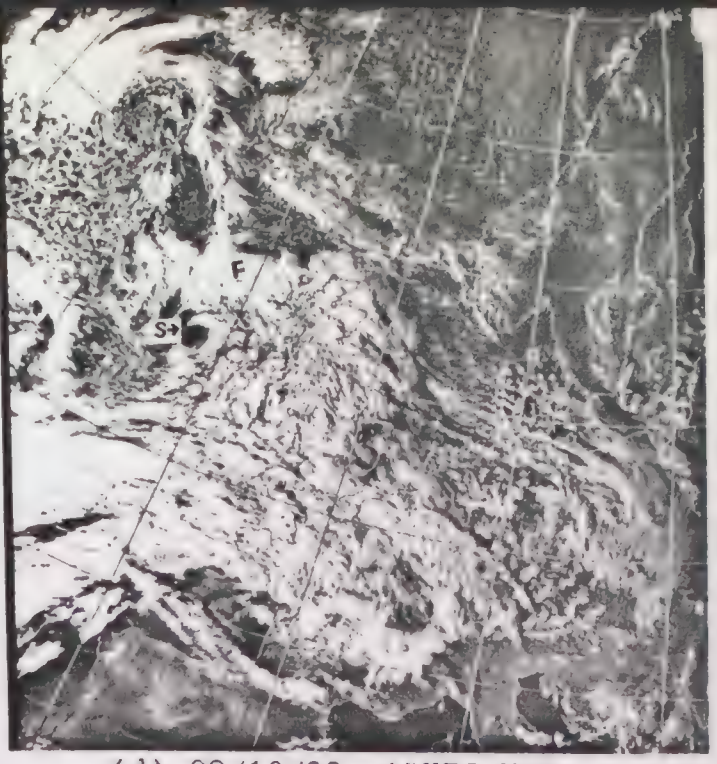
(a) 15/10/87 1630UTC IR



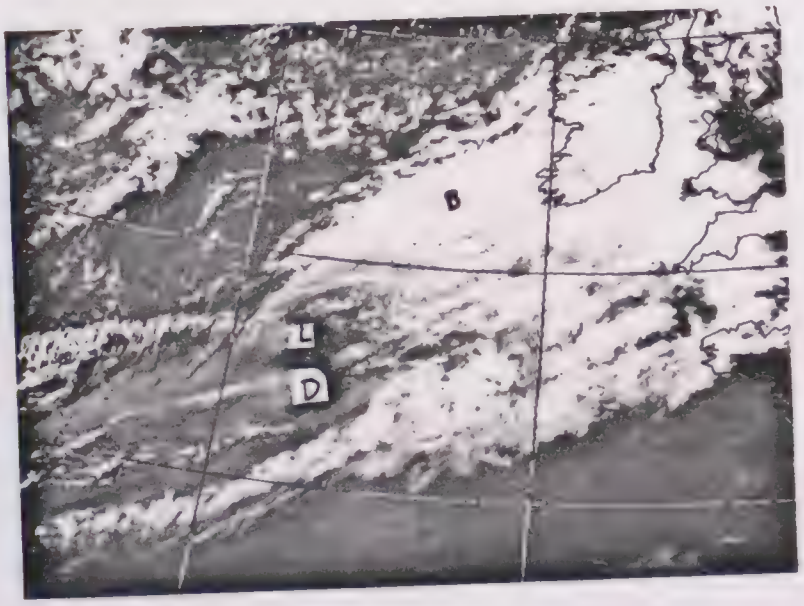
(b) 08/10/88 05UTC IR



(c) 08/10/88 15UTC IR



(d) 08/10/88 15UTC VIS



5.1.12

(e) 27/07/88 1630UTC IR

Clues for further development

* Cloud pattern persists for several hours
* C develops strongly convex poleward edge as in (a) and (b)
* C develops concave inner edge as in (a)

SURFACE LOW

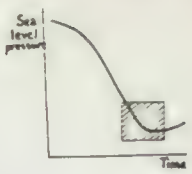
* Beneath cloud free wedge, just to the warm side of the rear portion of C
* Beneath a small swirl of low cloud S (most prominent on visible imagery), which can sometimes be seen on the inside of C. This marks the surface vorticity centre and is normally within 60nm of the depression centre e.g. (c) and (d)

For further discussion see Type 4A p28-43

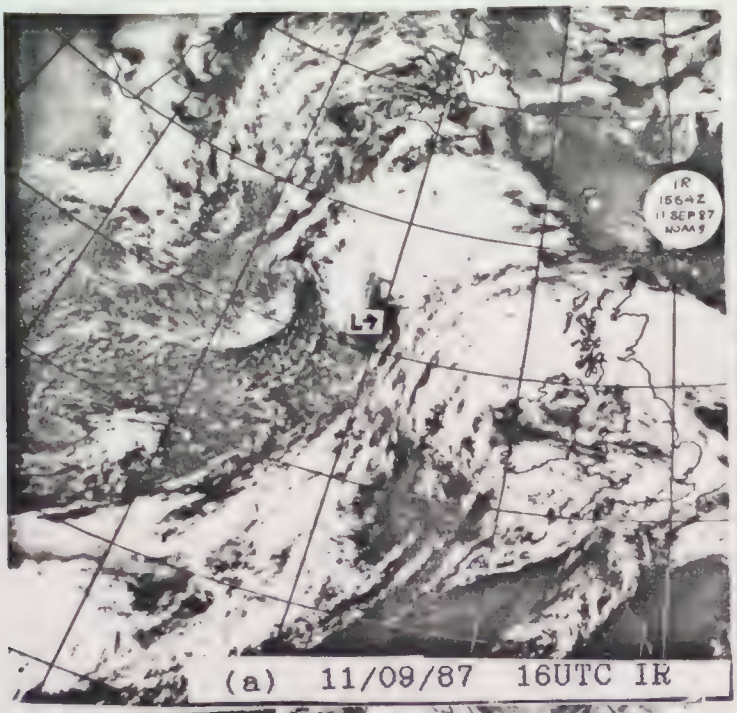
5.1.4 CLOUD SHAPES CHARACTERISTIC OF WELL DEVELOPED DEPRESSIONS (STAGE III)

In this section images are presented which show depressions:

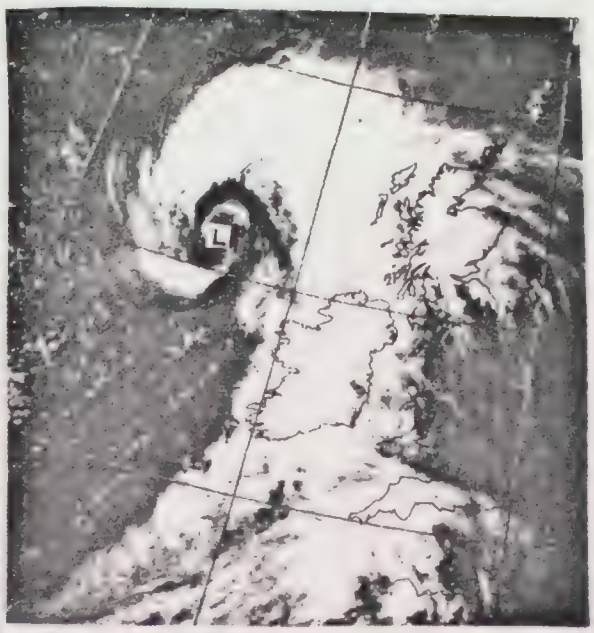
* late in the deepening phase (Fig. (a))
* that have finished deepening (Figs (b,c,d))



5.1.13

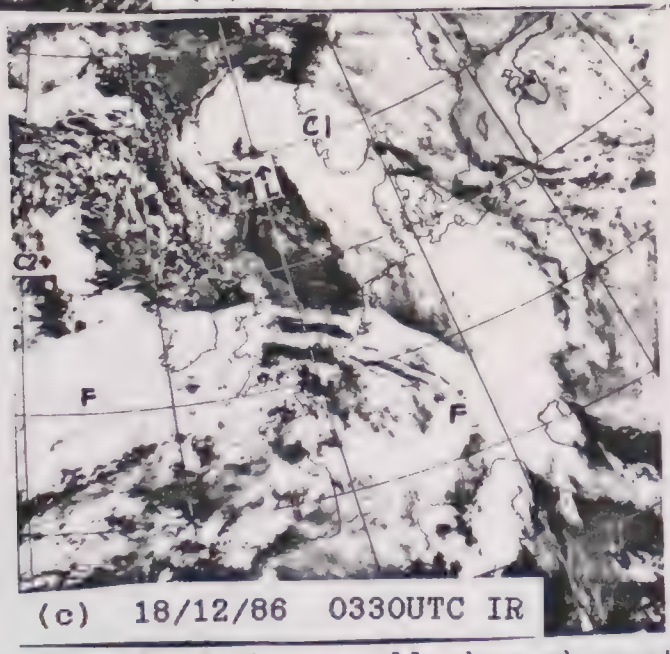


(a) 11/09/87 16UTC IR

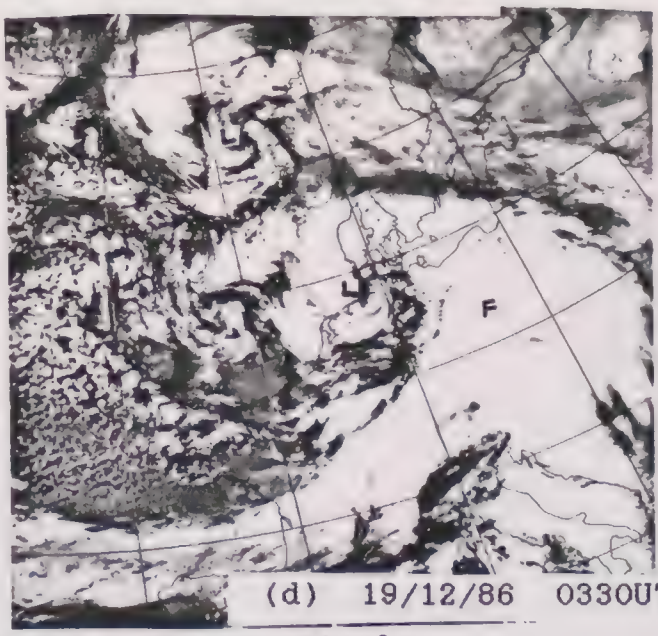


(b) 14/08/89 14UTC IR

5.1.14



(c) 18/12/86 0330UTC IR

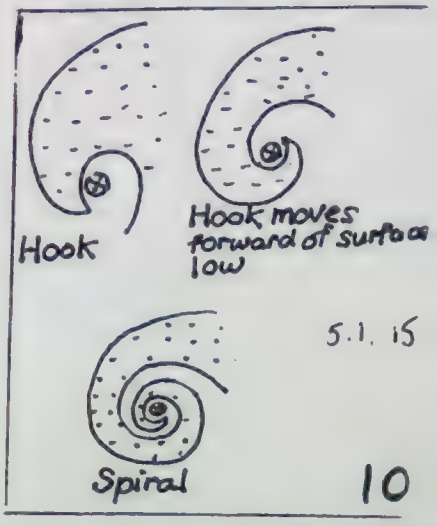


(d) 19/12/86 0330UTC

The cloud shapes all show characteristic hooks or spirals

* Once a hook of middle or upper level cloud has moved forward of the surface low (see inset), or a spiral has formed, deepening of the surface low has usually finished (See note)

In (a) the well-formed hook has not yet moved forward of surface low hence further deepening likely. In (b), (c) and (d) deepening is over since the hook has advanced forward of the surface low.



5.1.15

SURFACE LOW: In all cases this is situated

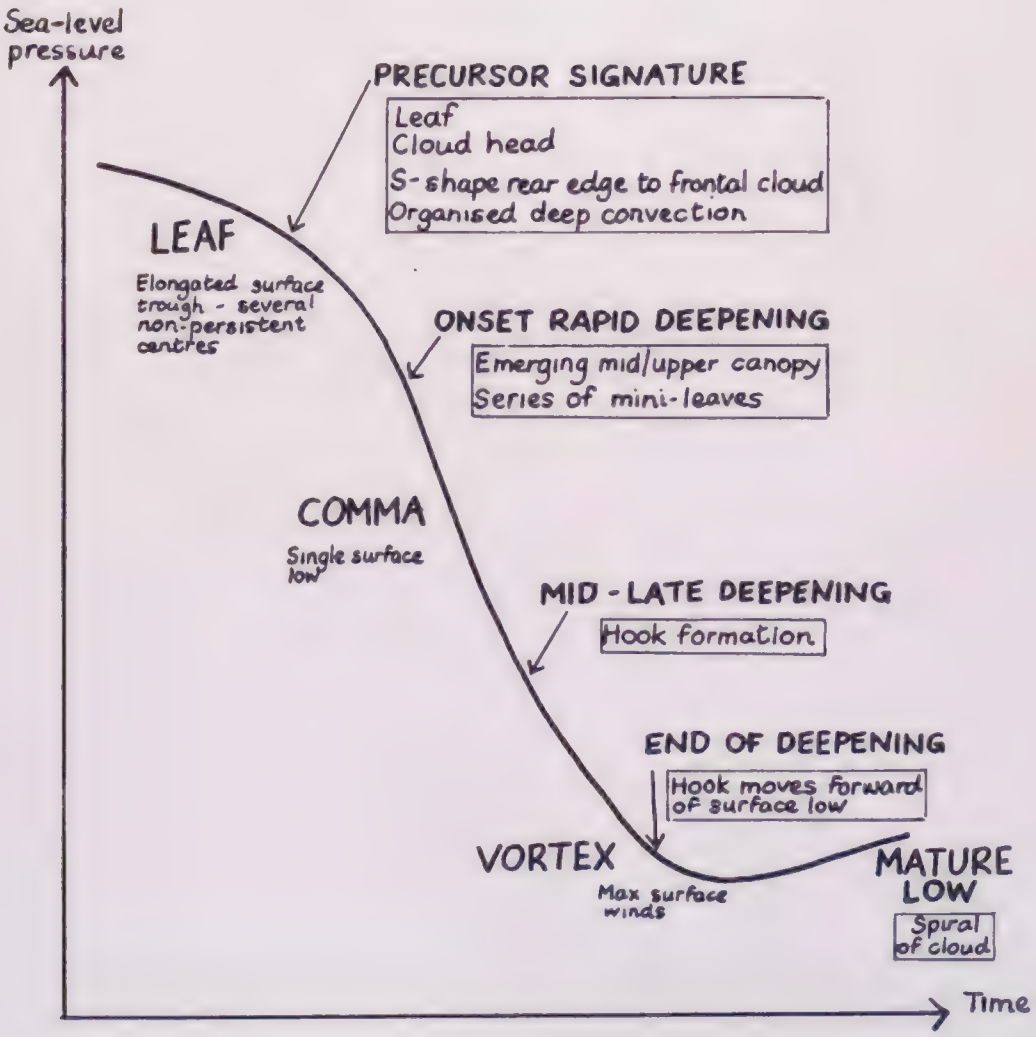
* within the dry slot on the inner edge of the hook
* at the centre of the spiral

Note: An exception appears to be when a strong northwesterly jet "spins up" the system giving it another surge of deepening late in its life cycle (possible in a Type 4B development)

CHARACTERISTIC CLOUD SIGNATURES SEEN AT VARIOUS STAGES OF CYCLOGENESIS

The graph shows a very idealised trend of central pressure against time, illustrating typical cloud signatures seen at various stages in the life of a cyclone. (In many cases the curve is far less smooth than that shown, especially if more than one short-wave trigger is involved in the cyclogenesis.)

To the left of the curve are the characteristic signatures introduced in Chapter 3. In section 5.2, a greater variety of signatures are introduced to take account of a realistic range of possible cloud patterns. Cloud patterns illustrated in the schematic life-cycles in section 5.2 correspond to the first three stages shown to the right of the curve.



5.1.16

CAUTIONARY NOTE

* Initial evidence of cyclogenesis usually seen only **after** deepening is underway

* Imagery does not tell us whether a system in its incipient stage will go through a complete life cycle to become a mature vortex

* At early stages of cyclogenesis there are a wide variety of likely cloud signatures, and exact location of the depression centre, if present, (say to within 200nm) is not always possible

* It is not possible to predict the exact deepening rate from imagery. We can usually, however, use imagery to distinguish signatures that preceed the most explosively deepening lows which may give hurricane-force surface winds

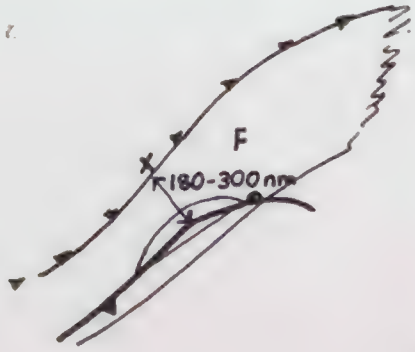
* It is easy to attach too much importance to eye-catching transient features on the imagery. (In real-time it is sometimes hard to assess whether such a feature will be transient or not until after the event!)

5.1.5

LOCATING SURFACE DEPRESSION CENTRE

SUMMARY OF RULES

(i) Cyclogenesis emanating from beneath frontal cloud F along or to warm side of the main jet

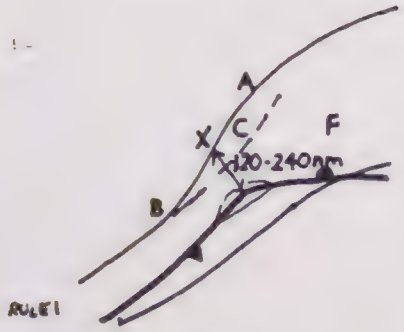


Prior to major deepening an elongated pressure trough usually lies along the axis of the frontal cloudband. Several minor low pressure centres are likely but they will be difficult to follow even over a dense data network.

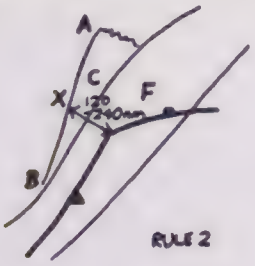
RULE 0 The "centre of gravity" of the elongated low lies beneath the frontal cloudband F adjacent to the inflection point X of the S-shaped rear edge, some 180-300nm in from the edge. *

* Note: If F is narrow i.e. < 240nm wide, place low in middle of cloud band

During rapid deepening, the mid or upper level cloud extension C emerges from beneath the frontal band or is revealed as the surge region (dashed) moves forward. By this stage a single centre is usually present. To locate the depression centre or the centre of gravity of the minor lows:

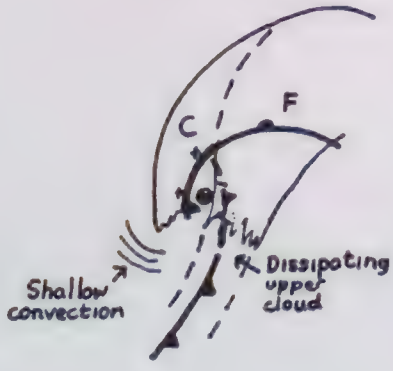


RULE 1 Consider the rear edge of the cloud as an S-shape. Locate X, the inflection point of the S. Draw a line from X into the cloudband at 90deg to the surge line. The centre will lie 120-240nm in from the rear edge. *



RULE 2 If it is not easy to locate the infection point (e.g. if AB is a straight edge), then find the point X midway between the apex A of the extension and the point B where it tucks beneath F. The centre lies 120-240nm in from the rear edge along a line projected from X at 90deg to the surge.

RULE 3 Look for substantial thinning of the upper cloud shield immediately upwind of the low.



As C continues to emerge from beneath F, the depression centre remains at the same distance from the rear edge of C.

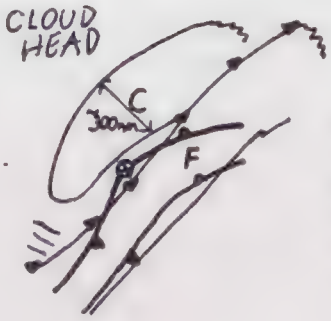
RULE 4 When C has become well separated from F, revealing warm cloud tops (usually within 10deg of surface temperature) along its inner edge, a single low centre lies in the new dry slot, beneath the warmest cloud tops on the inside of C, towards its upstream end.

3

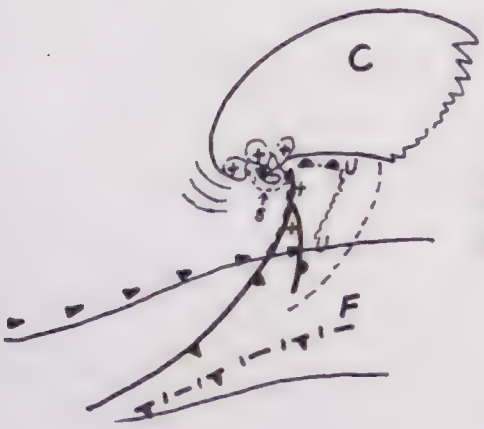
5.1.17

(ii) Cyclogenesis emanating from cumuliform or stratiform cloud C on the cold side of the jet

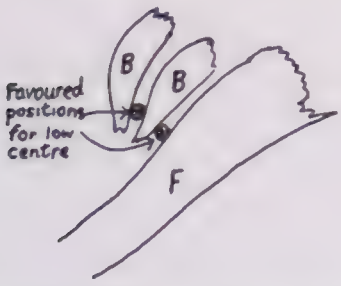
* At the rear edge of C near the most rapidly growing convective elements. These will often "radiate" from the position of the low centre



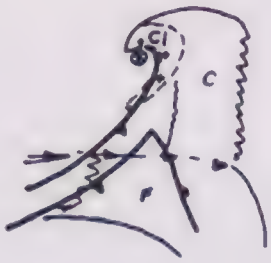
SURFACE LOW - elongated and sometimes complex; lies beneath warm cloud tops on inside rear portion of C, or beneath the dry (cloud-free) wedge if one is present as in right hand figure.
(F sometimes thin or absent)



RULE 7 A small swirl of low cloud S can sometimes be seen on the inside of C which marks the surface vorticity centre - most prominent on visible imagery and is normally within 60nm of depression centre.



* Beneath the warmest cloud tops along the inside edge of one of the mini-leaves, B



* Within a small comma-shaped cloud area Cl situated at the rear of C

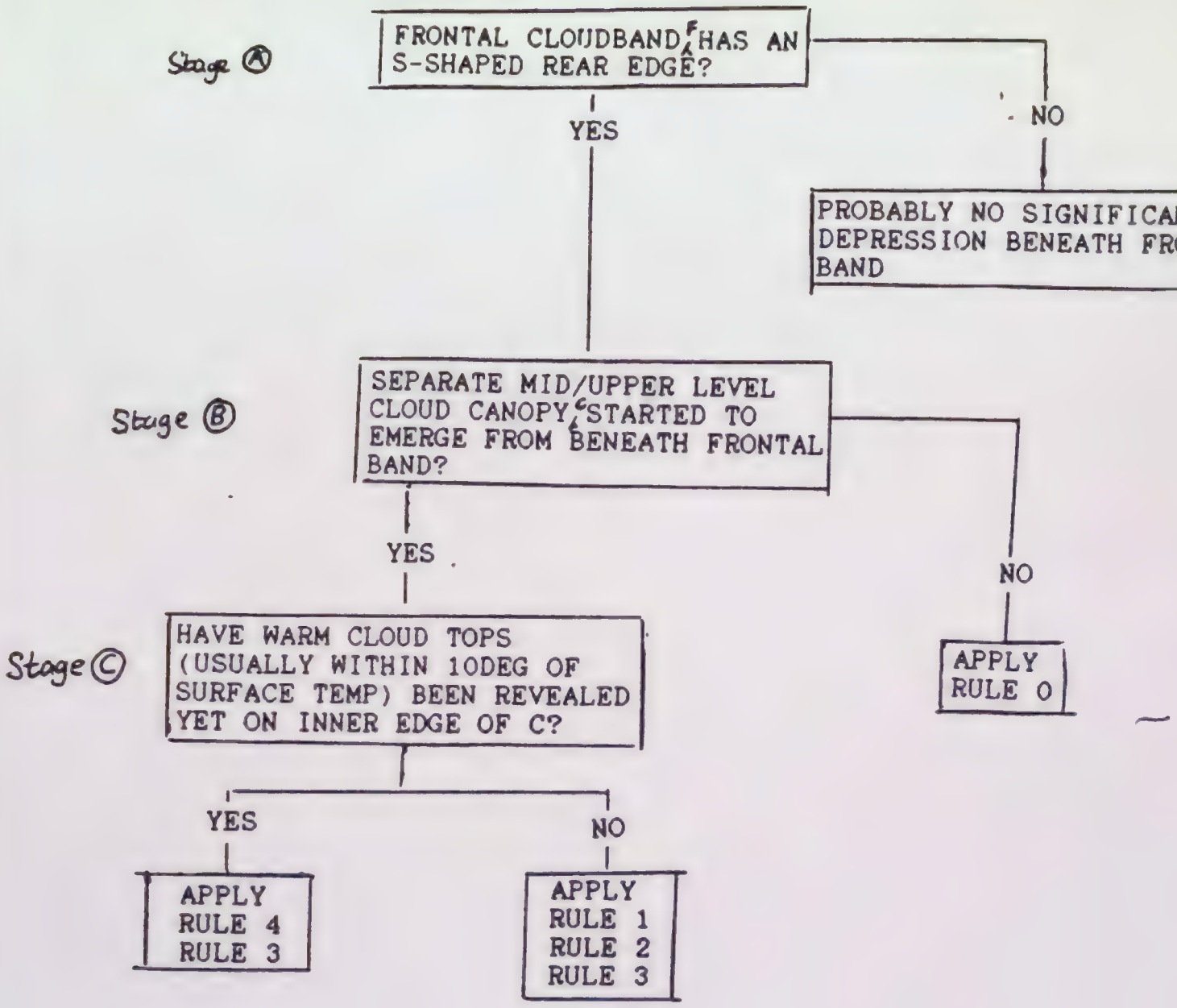
5.1. 18 -

(iii) Well-developed or mature depression

5.1. 19

* within the dry slot on the inner edge of the hook
* at the centre of the spiral

LOCATING THE DEPRESSION CENTRE



5.1.20

Precipitation distribution

(A) Prior to cyclogenesis, precipitation distribution is typical of rearward-sloping ascent (Ch. 4).

(B) As C emerges from beneath F, there is usually an expanding rainfall area adjacent to C, lying at least partly beneath beneath F.

(C) Once the hook C has formed, heavy rain occurs along its inside edge beneath the steep gradient of cloud top temperature. Meanwhile rainfall weakens where F dissipates.

5.1.6

SUMMARY OF INDICATIONS FOR EXPLOSIVE CYCLOGENESIS

UPPER AIR PATTERN

* Flat, slightly confluent upper trough with strong flow extending around the base (Type 4A)

* Jet ahead of the upper trough exceeds 140kn

* Separate (trigger) jet streak may be approaching from upstream

SATELLITE IMAGERY

The cloud signature that is a reliable precursor to explosive cyclogenesis is the "CLOUD HEAD"

* **A well-defined cloud head is a reliable precursor of explosive deepening** (usually well in excess of the "bomb" criterion of 24mb per day), **with hurricane-force surface winds some 18-24 hours after the signature first appears**

It is characterised by two adjacent areas of layered cloud C and F separated by a narrow cloud-free wedge. To be classified as a cloud head the **first two** of the following criteria on imagery must be met:

(1) CLOUD AREA C

- **Very broad** in the direction of the cold air, at least 300nm
- **Convex poleward edge**
- Must consist mainly of **layered cloud**
- Gradual progression from **warm cloud tops on equatorward side to cold cloud tops at poleward limit**. Densest cloud beneath warm tops, poleward limit semi-transparant

(2) **Narrow cloud-free region between C and F** - the "dry wedge"

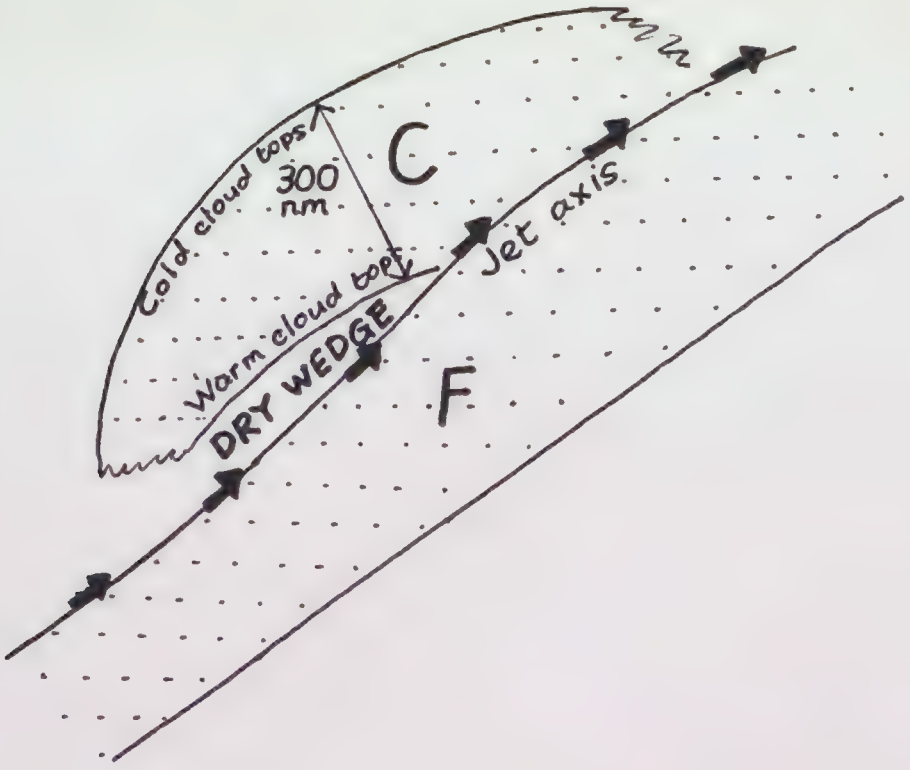
- **Water vapour imagery** often shows this dry wedge or "dark band" to be **drying (darkening) with time** several hours prior to (or during) the onset of explosive deepening

(3) CLOUD AREA F

* In some cases this is very tenuous consisting of thin cirrus fibres travelling along the jet, and in other cases is extremely broad and dense with embedded instability. **The presence or otherwise of F appears to have little bearing on the instensity of cyclogenesis**

* In addition, there is often (during autumn and winter), deep open cellular convection poleward of C, which appears to undercut C.

- Satellite movieloops show convection to be continuously digging beneath C



RAPID DEEPENING is ACCOMPANIED by C becoming increasingly convex and evolving into a hook. At this stage a new region of very strong winds is forming near the base of the hook

NOTE:

1. **To be accompanied by explosive deepening, the cloud head must remain well-defined throughout the evolution.** Exceptionally, the signature (cloud area C in particular) may become fragmented, indicating early termination of the development cycle (see pXXX) 54-57 Section 5.3

2. For the above reason **it is unwise predict explosive cyclogenesis from a single picture. A sequence of pictures or a movieloop gives a better perspective.** The upper flow pattern and associated forcing mechanisms must be studied in conjunction with the imagery for clues to the synoptic development.

Examples p 3 & 4

F 5.1. 21

5.2 ARCHETYPAL CYCLOGENESIS TYPES IN IMAGERY AND ANALYSIS

5.2.1 DECISION TREE APPROACH FOR DETERMINING CYCLONE TYPE

1. Forecaster should look in an area within and upstream of long wave trough.

2. Forecaster should use satellite imagery and upper-air winds to identify multiple jet streams, or single jet stream, confluence or diffluence.

3. Look at decision tree to identify long-wave flow pattern.

4. Identify a "trigger" short wave trough or jet streak, if any, upstream of long wave trough. (This trigger may not always be evident on imagery or upper-air pattern.)

Consultation of the summary of initial cloud signatures in section 5.2 will help to determine when cyclogenesis is about to commence or is under way.

Note: In the event of a long straight flow pattern containing no significant troughs see section 5.2.2 category "elongated flow, infinitesimal trigger".

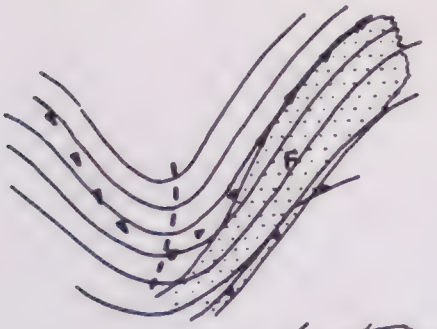
A cyclone will not necessarily complete a whole life cycle · eg the system may move into part of the upper air pattern that no longer supports cyclogenesis, in which case the cloud signature will break up eg pp. 54-5; see 5.3

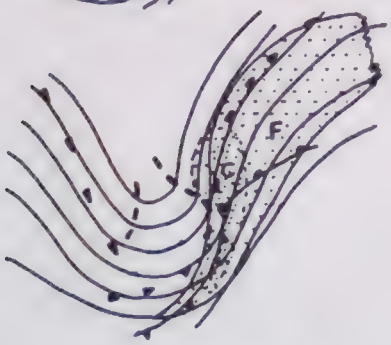
5.2.2 THE ARCHETYPES

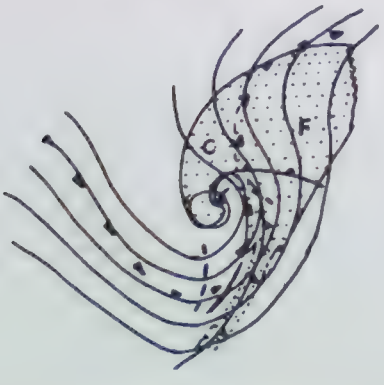
TYPE 1 MERIDIONAL TROUGH CYCLOGENESIS

* Short wave trigger appears to form on forward side of major trough - amplitude from trough to ridge normally exceeds 13deg latitude

* Short wave may have arrived from behind the major trough, but cannot be detected readily on imagery or upper air charts





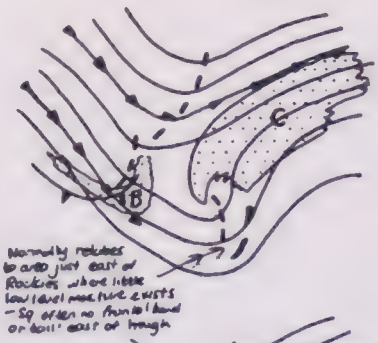


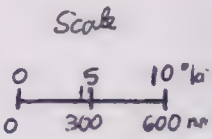
TYPE 2 SPLIT FLOW CYCLOGENESIS

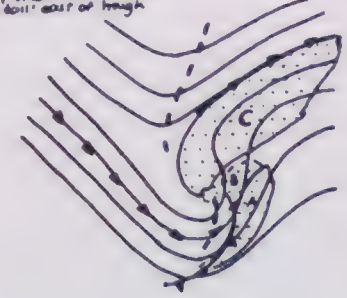
* Double jet or split jet

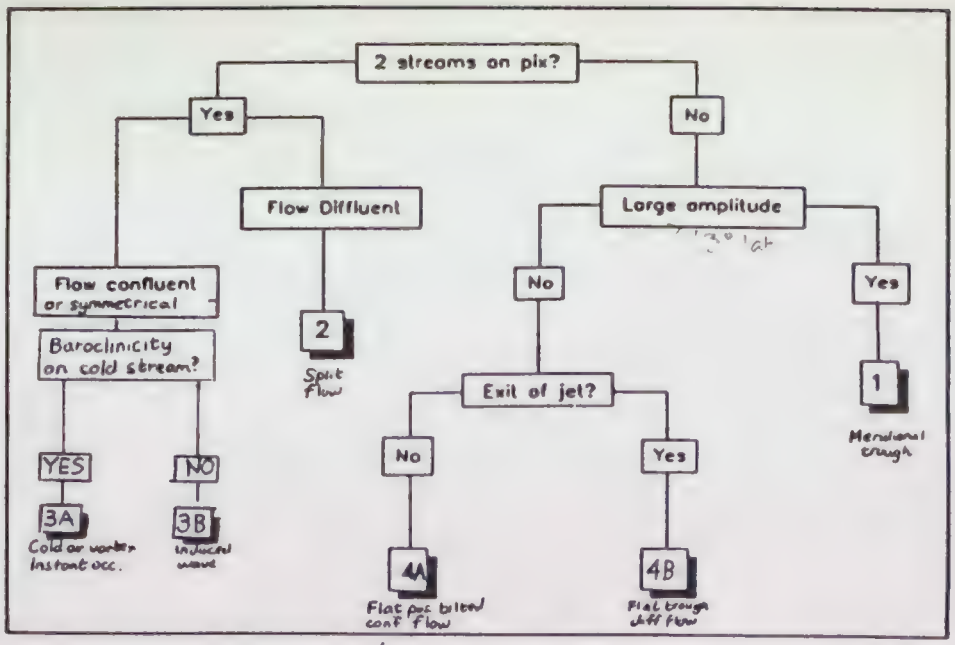
* Short wave feature B moves through equatorward jet and around slower moving cut-off low

* Most common east of Rocky Mountains - rare over oceans









Decision tree adapted from McLennan & Neil 1988

TYPE 3

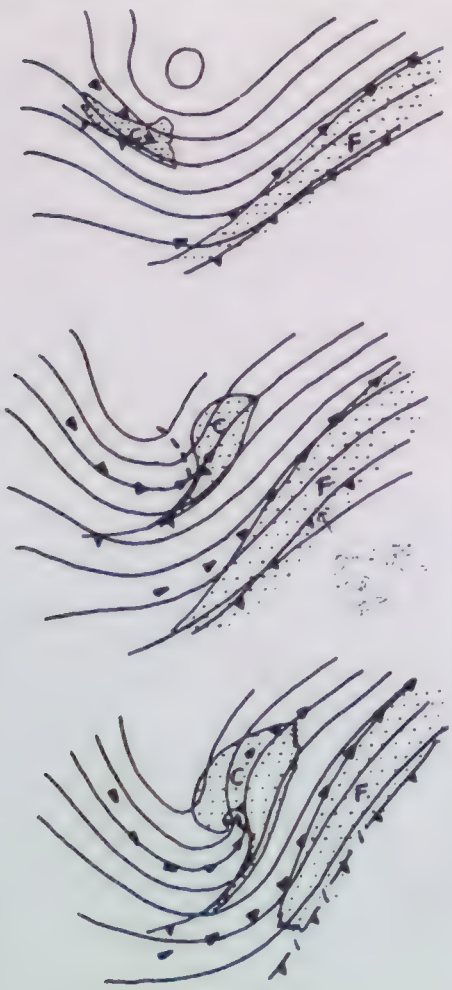
* Broad-scale rounded upper trough - symmetrical or slightly confluent upper flow containing short waves

TYPE 3A

* Short wave moves through marked baroclinic zone to rear of upper trough, accompanied by expanding cloudmass C

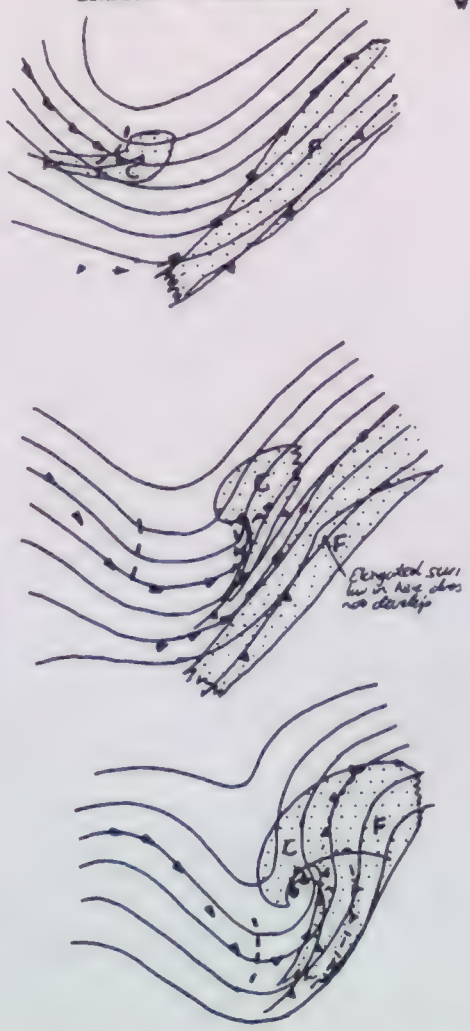
* **Cyclogenesis occurs in conjuction with the short wave, on the cold side of pre-existing frontal band F**

COLD AIR VORTEX CYCLOGENESIS



* C stays sufficiently remote from F so that the two features do not interact

INSTANT OCCLUSION



* C moves sufficiently close to F so that the two cloud features interact and merge

TYPE 3B INDUCED WAVE CYCLOGENESIS

* Short-wave feature C originates on cold side of established jet to rear of upper trough - possesses little baroclinicity

* Cyclogenesis takes place beneath frontal band F and not in conjunction with C

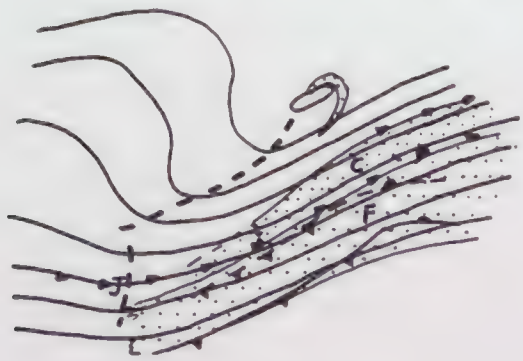
TYPE 4A FLAT TROUGH - CONFLUENT FLOW

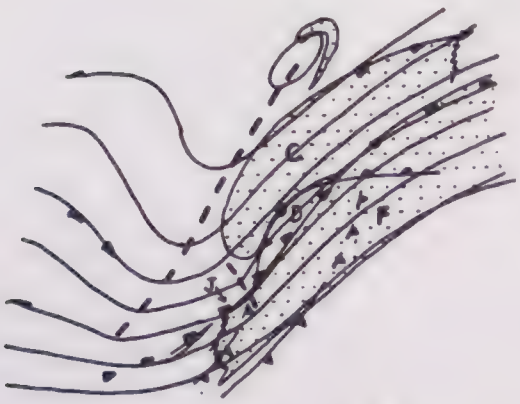
* Short-wave trigger (or jet streak) either moves around the flat confluent trough or originates within the strong zonal flow equatorward of the trough axis

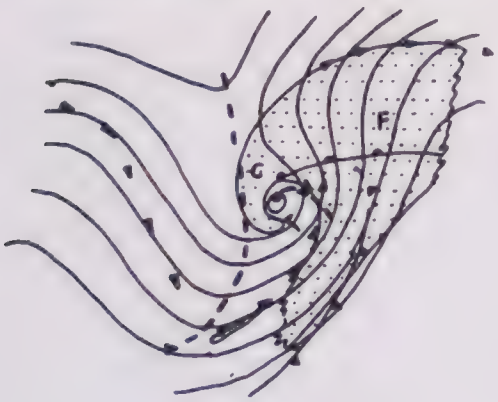
* Short wave often not detectable on imagery or upper air charts until cyclogenesis well underway

* Imagery sequence sometimes similar to Type 1

MOST COMMON SCENARIO FOR EXPLOSIVE CYCLOGENESIS





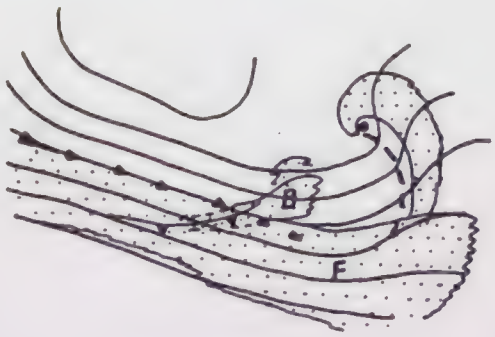


TYPE 4B FLAT TROUGH - DIFFLUENT FLOW

* Trigger for cyclogenesis is the left exit of an advancing jet streak

* Cyclogenesis takes place within an increasingly diffluent large scale pattern

* Typically occurs at the eastern end of a zonal flow just west of an "omega block"



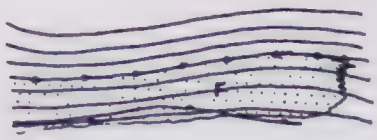
TYPE 4B SPECIAL CASE Elongated airstream - infinitessimal trigger

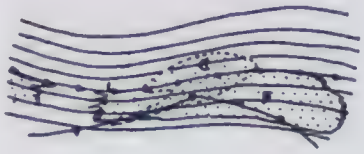
* No significant short wave detectable on imagery or upper air contours

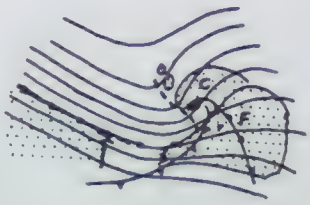
* Short wave amplifies within the baroclinic zone but is concealed beneath the cirrus shield

* Adjacent cold air convection initially undisturbed

* Typically occurs in zonal flow, well upstream of a block







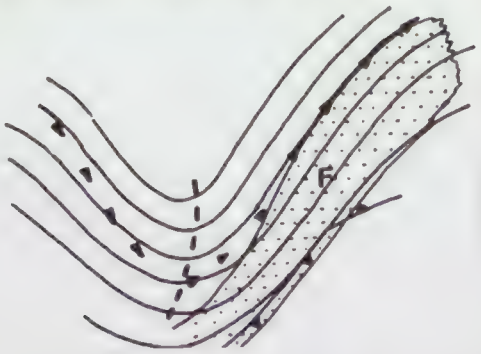
5.3 EVOLUTIONS OF ARCHETYPES OF CYCLOGENESIS

5.3.1
TYPE 1 MERIDIONAL TROUGH CYCLOGENESIS

IDEALISED 300MB FLOW AND CLOUD OUTLINE

IR IMAGERY

5.3.1 (a)



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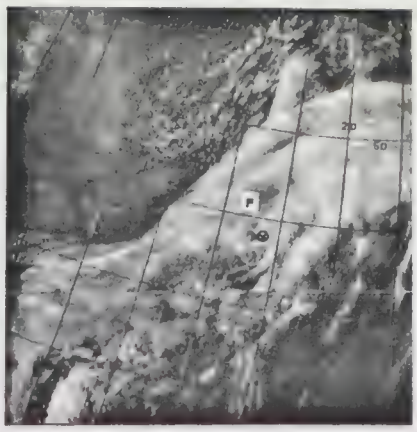
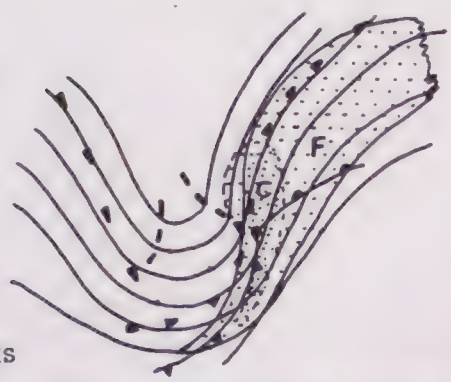


PRECURSOR

* Large amplitude upper trough - amplitude from trough to ridge typically exceeds 13deg latitude (Neil criterion)
* Broad band of frontal cloud F ahead of a major upper trough
* The sharp poleward edge begins to exhibit an S-shaped rear edge
* Jet axis along poleward boundary
* Convective cloud in the cold air may show little or no clustering

5.3.2 (a)



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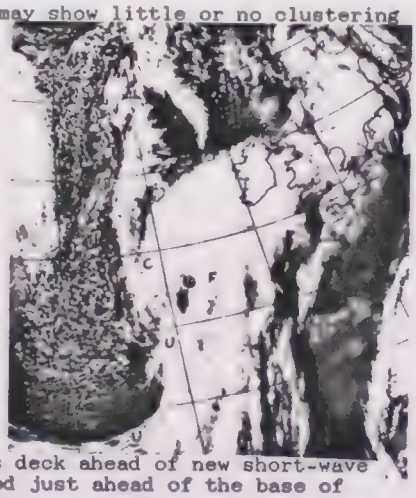
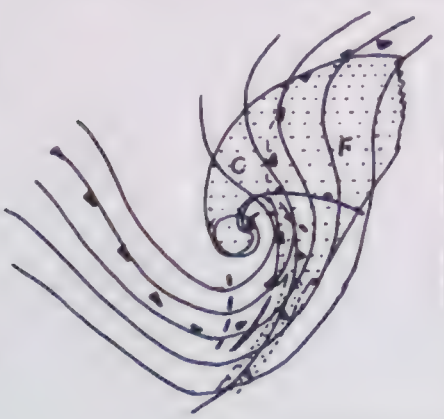


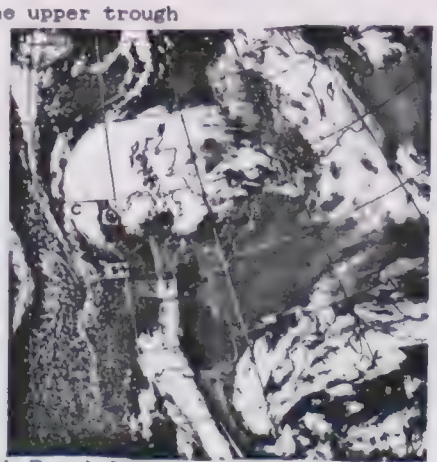
CYCLOGENESIS UNDERWAY

* Comma C initially forms beneath cirrus deck ahead of new short-wave trough. This trough appears to have formed just ahead of the base of the major trough
* C, which consists of upper or middle level cloud, emerges from beneath F
* F begins to thin, immediately upwind of C (behind the short wave)
* Substantial cyclogenesis will usually already have occurred beneath F by the time C begins to emerge
* Further short waves may move around the upper trough

5.3.3 (a)



(b)



MATURING

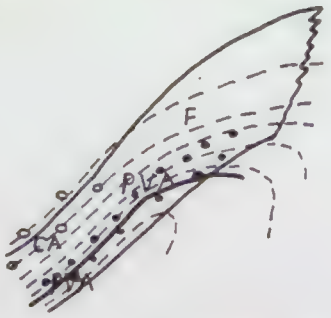
* C extends further from beneath F and forms a hook around the surface low, by now well developed
* Cloud free slot between C and F
* Continued dissipation of upper and middle cloud within F upwind of C
* More cirrus may grow along the jet axis further upstream of the depression as further short waves move onto the forward side of the upper trough, perhaps triggering a wave on the cold front

ADVECTION, VERTICAL MOTION AND THERMAL FIELDS

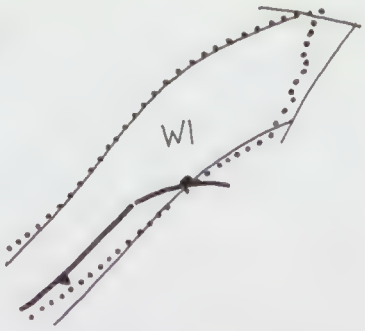
AIRFLOW MODEL

SURFACE ANALYSIS AND PRECIPITATION

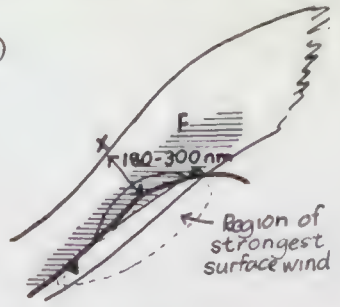
1 (c)



(d)



(e)



* F formed by ascending warm conveyor belt W1 originating at low latitudes

* The ascending motion parallel to the front is associated with an elongated region of PVA ahead of the major upper trough

* Strong thermal gradient parallel to front

* Thermal advection relatively weak, although CA becoming established behind cold front

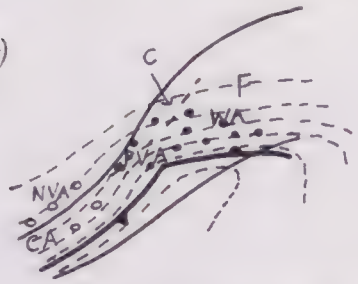
* Broad rain area beneath F associated with W1. Pattern typical of that associated with "rearward sloping ascent" (see Ch. 4)

* Elongated surface low along axis of F - usually contains several small centres which are difficult to track

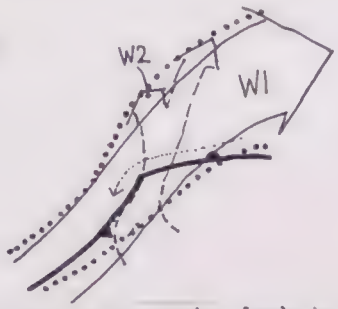
* If F is narrow (less than 240nm), place low in the middle of cloud band

* Strongest surface winds found in warm sector

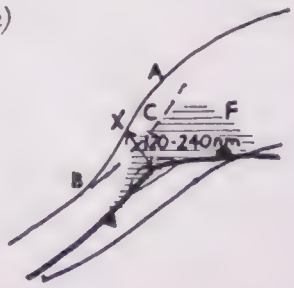
2 (c)



(d)



(e)



* PVA now concentrated ahead of the short wave trough - leads to strong ascent over and ahead of developing low near cloud extension C

* Weakening upward motion behind the low

* Onset of WA contributes to ascent ahead of the low; CA to its rear enhances descent

* Thermal gradient increases ahead of warm front

* Secondary warm conveyor belt W2 associated with formation of cloud extension C, ascends strongly as it emerges from beneath W1

* W2 probably consists of highly modified polar air (brought equatorwards in the wake of a previous depression) which has subsequently been engaged into the low level flow beneath the forward limit of W1 (ref. Grotjahn and Wang 1989)

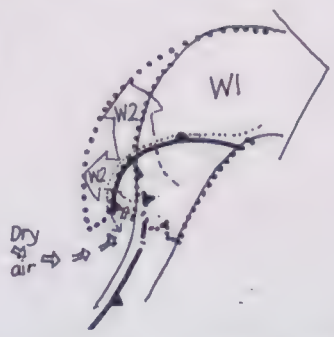
* Heaviest precipitation adjacent newly formed cloud area C; associated with strong ascent of W2

* Weakening of rain upwind of C where ascending motion has reduced

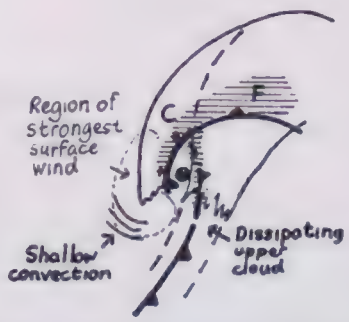
* Surface low consolidates into a single deepening centre; position as shown

3 (c)

(d)



(e)



* The strong thermal gradient ahead of the warm front extends around rear of depression forming a "bent back warm front"; it lies along the inside of C. A small pool of warm air sometimes becomes secluded beneath dry slot

* Near depression centre, original cold front loses its thermal gradient; it is now effectively an upper front

* Narrow band of strong ascent links C and F along main thermal gradient; dominated by PVA in vicinity of C and WA beneath F

* Shallow cold conveyor belt moves around the west of the depression in the strong low level flow - seen as a trail of low cloud emanating from beneath tip of C

* Middle and upper level dry air entrained into rear of developing system to form the dry slot

* Heaviest precipitation along inside edge of C and beneath F where W2 ascends over marked frontal zone

* Embedded mid-level convection cells; thunder possible - due to potential instability release where dry air overruns W2

* Precipitation along cold front continues to weaken. Watch for further wave development later, that may enhance the rainfall

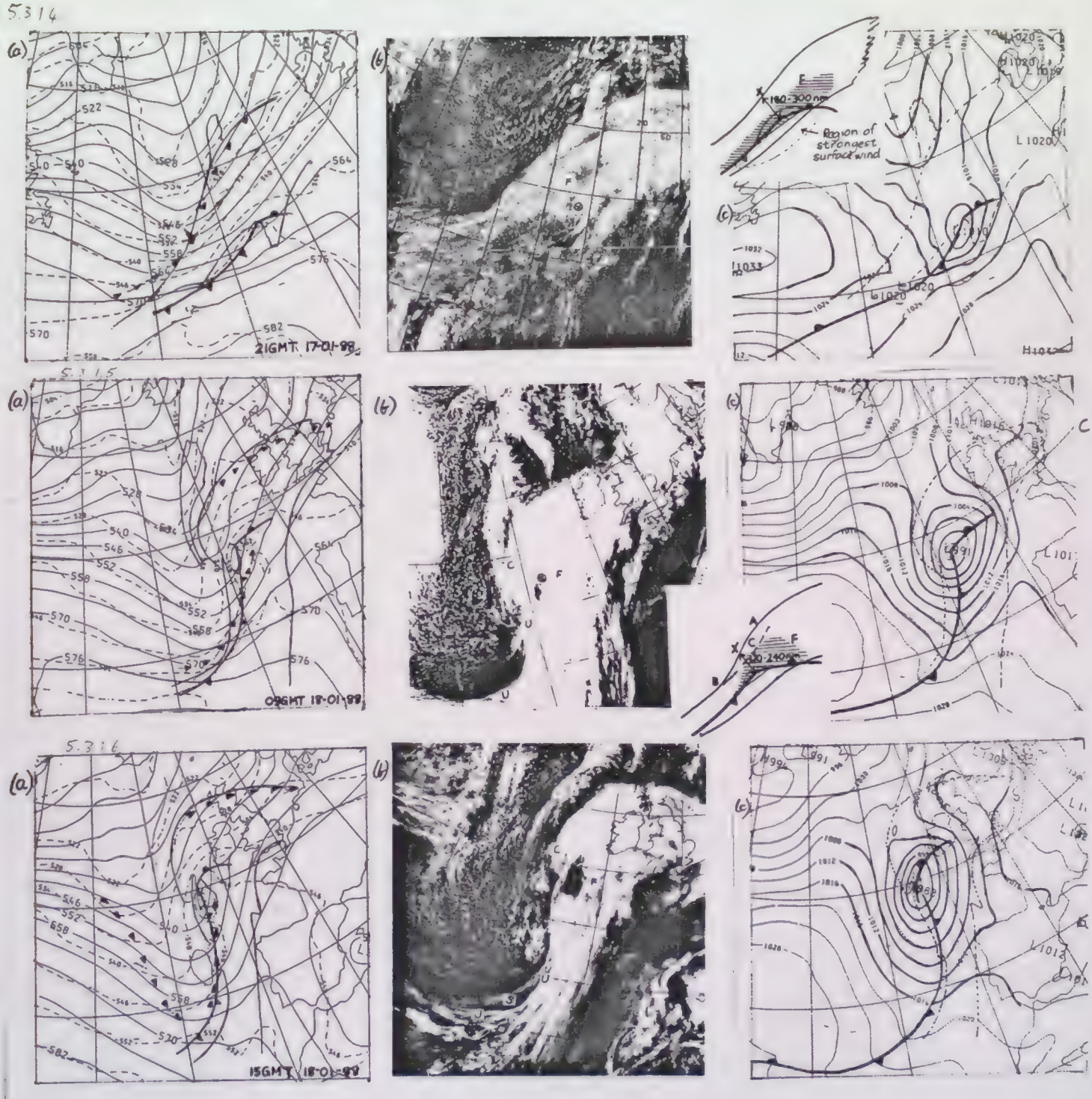
* Surface low beneath dry slot

* Strongest surface winds now found near base of hook following passage of bent back warm front - streets of shallow convection just behind C usually indicate gale force winds

EXAMPLE OF EVOLUTION OF TYPE 1 CYCLOGENESIS

This case illustrates many aspects of the evolution shown schematically on ~~p.xxx~~ pp. 1-2.

5314



● Depression centre

* Thermal gradient increases ahead of the warm front and weakens considerable across the cold front near the depression

Differences from schematic:

* This case illustrates how the jet axis, rather than remaining continuous across the depression, often "fractures" above the depression centre during cyclogenesis, with a separate jet forming along the forward limit of the upper cloud shield

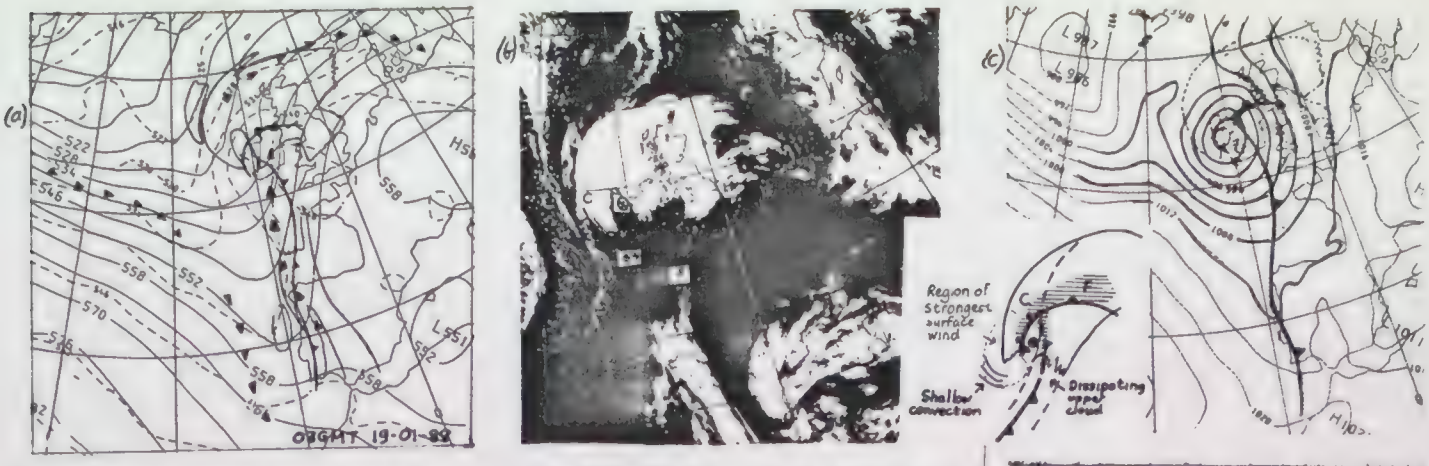
Features worthy of note on the imagery are as follows:

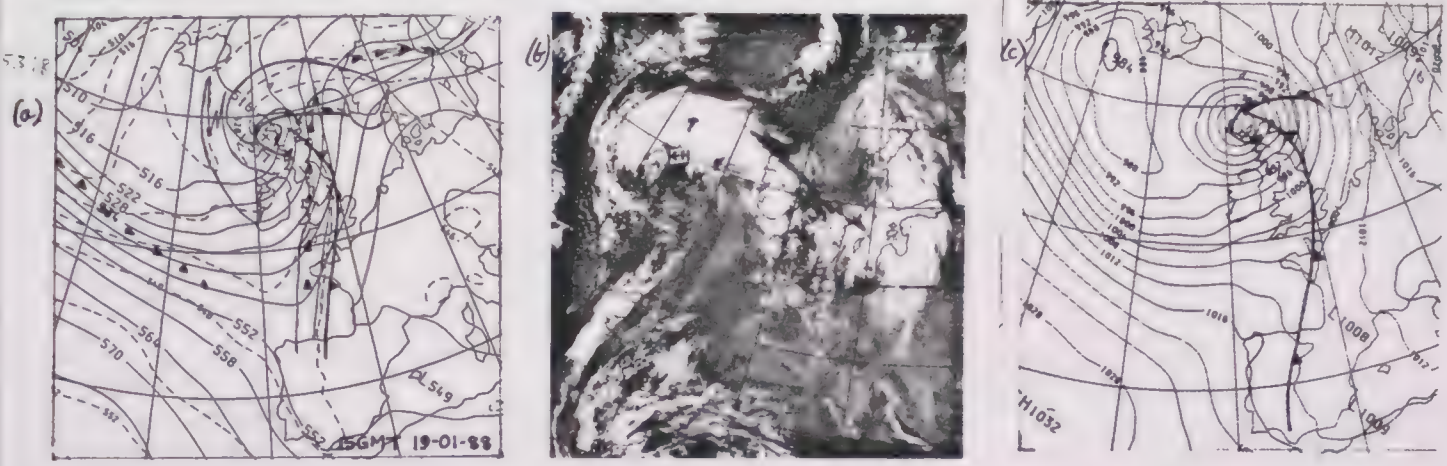
* Distinct S-shaped rear edge to upper cloudband F at 21UTC 17/01/88

* Well-marked cloud area C progressively emerging from beneath F at 09GMT and 15UTC 18/01/88

* Pronounced dissipation of upper and middle level cloud across F immediately upwind of C. This process continues so that by 03UTC 19/01/88, only a narrow band of warm cloud tops delineates the cold front

53B





* A swirl of low cloud S has wrapped around the depression by 03UTC 19/01/88. Since the hook of upper cloud C has still not moved forward of the low, further deepening is to be expected

* By 15UTC 19/01/88, the presence of a hook or comma of upper cloud H forward of the low suggests that deepening is now complete

Locating the surface depression centre

21UTC 17/01/88 - A rather elongated depression centre lies some 300nm in from the inflection point X (see inset) of the poleward edge of F

09UTC 18/01/88 - The deepening depression centre lies adjacent to cloud extension C, midway between the apex A, and the point B where C tucks beneath F

03UTC 19/01/88 - Depression centre located beneath dry slot. The surface analysis and weather at this time, in particular the bent-back warm front is shown in more detail on p~~XXX~~6

This sequence also illustrates the formation of a cut-off low at the base of the upper trough. First signs on the imagery are seen at 09 and 15UTC 18/01/88 as the cirrus edge UU moves forward revealing a sheet of low cloud constituting a shallow moist zone (SMZ). Eventually (03UTC 19/01/88 image), a small convective circulation X forms around the vorticity maximum at the base of the trough (see NWP diagnostics p~~XXX~~7 - 8.

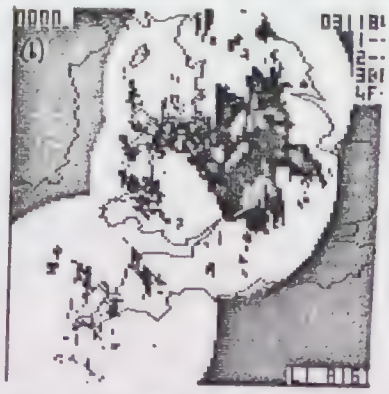
TYPE I MESOSCALE WEATHER

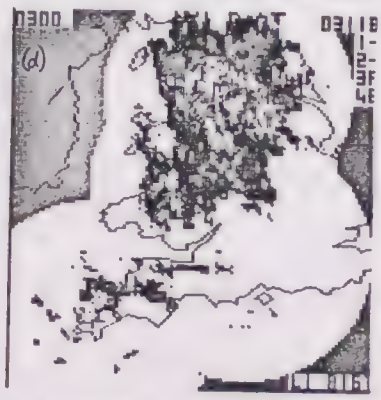
This case is chosen to demonstrate the precipitation distribution and surface analysis in the vicinity of a depression which developed over the UK observing network. Cyclogenesis is associated with a slow moving cold front on the forward side of a large amplitude upper trough

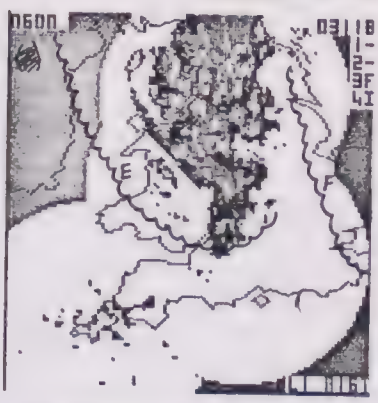
5.3(a)

5.3(c)

5.3(e)







IR IMAGERY (Figs a,c and e)

* Cloud area C (mid-level tops) had formed on western side of cloud area F, giving early warning of possible cyclogenesis

* Cloud tops of C are cooling; confirming likely cyclogenesis

* During cyclogenesis, almost complete dissipation of upper and middle cloud occurs across F

* Following dissipation of upper cloud, the ragged inner edge of C is revealed, resulting in the hook-shaped cloud formation C (particularly prominent on WV image), characteristic of a well-developed depression (Fig(g))

RAINFALL DISTRIBUTION (Figs b,d and f)
(radar image covers boxed area on IR image)

* Expanding area of rain adjacent to cooling cloud area C

* Rainfall becomes heavy, widely exceeding 4mm/h

* Heaviest rain lies along inner edge of hook C, beneath strongest gradient of cloud top temperatures. Some thunderstorms also occur within this region.

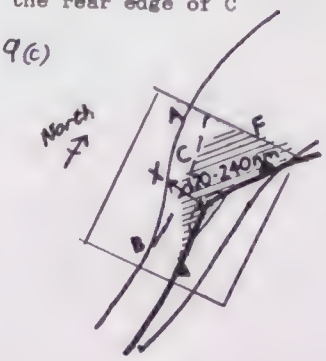
SURFACE ANALYSIS (refer to schematic insets) (boxed area refers to boxed area on IR image)

This case illustrates the following guidelines for locating the surface low centre (detailed rules in Sec. 5.1.3, p.13)

* An elongated pressure trough is present in Fig. (a) containing a number of small non-persistent low centres.

* The centre of gravity (CG) of the lows lies over eastern England, in this case 160nm in from the point X at the rear edge of C

9(c)

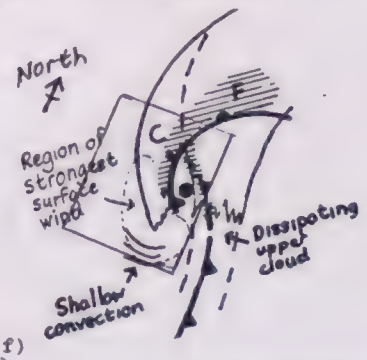


* As C evolves into a hook (Figs (c) and (e)), the complex depressions consolidate into a single centre, located beneath warm tops on the inside of C.

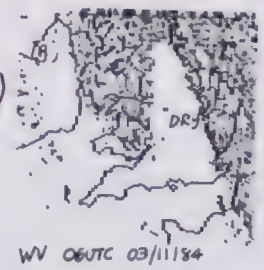
* The CG of the centres remains at the same distance from apex A throughout the sequence

* The depression centre is located immediately ahead of the region of upper cloud dissipation

11(c)



11(d)



WV 0600UTC 03/11/84

NOTE:

(1) The movement of the depression centre can be extrapolated from successive positions of cloud area C. In this case C, and therefore the associated developing depression and rain area, is becoming very slow moving. This suggests that areas currently within the rain area can expect further large accumulations.

(2) In the winter season especially, heavy rain can readily turn to snow in the cold air beneath the inner edge of C. In the British Isles this possibilty should be considered for areas where the wet bulb freezing level is 3000ft or less above the surface prior to onset of rain.

5

SURFACE ANALYSIS AND WEATHER

SEQUENCE OF OBSERVATIONS OVER AND AROUND DRY SLOT

5.3.1\2

Sequence of observations from Cork airport (elevated location near south coast of Ireland) 16GMT 18/01/88 to 08GMT 19/01/88.

The schematic diagram on the left shows the location of each observation relative to fronts and the cloud boundary (from IR imagery) spanning the times corresponding to the third and fourth images on pXXX).

The main features are as follows:

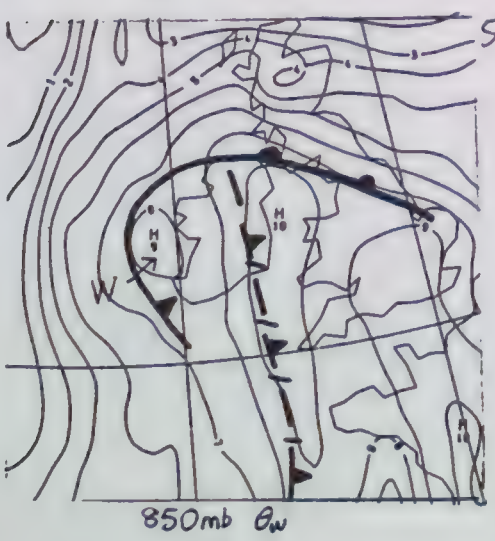
* Moderate rain ahead of the warm front beneath cold cloud tops

* Very little rain associated with the dissipating cold frontal cloud (See Note 2)

* The most significant changes in wind, temperature and pressure accompany the bent-back warm front along the inside of the hook

* The frontolysing cold front is marked by lifting and breaking of much of the low stratus but only a small drop in dewpoint

* NWP analysis of θ_w for 03UTC 19/01/88 (corresponding with fourth IR image in the sequence on p~~XXX~~27) confirms the frontal features shown in the figure and in addition, the pocket of secluded warm air near the depression centre



5.3\13

NOTE 1 The configuration of the fronts and the sequence of observations shown above is not unique to Type 1 cyclogenesis events. Further examples are shown in conjunction with Type 3B (p~~XXX~~27) and Type 4A (p~~XXX~~37)

NOTE 2 - This sequence of observations does not sample the region of heavy rain on the inner edge of the hook since just the decaying tip of the hook passed over the station.

DYNAMICAL PROCESSES ACCOMPANYING TYPE I CYCLOGENESIS

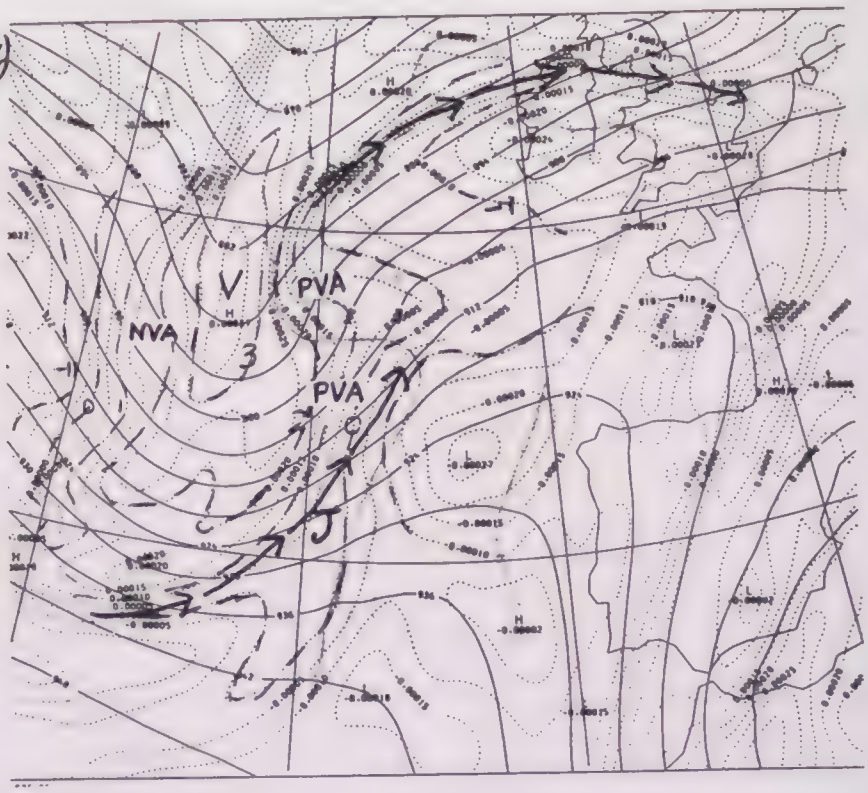
The major changes that occur to the cloud pattern on IR imagery from 18-19/01/88 can be explained with reference to NWP model vertical velocity, vorticity, thermal advection fields and humidity fields.

The vorticity maximum V within the major upper trough plays a crucial role throughout the development process - the partitioning of the upward motion field on the forward side of V due to effects of thermal advection around the developing depression provides a means for explaining the cloud evolution (see note).

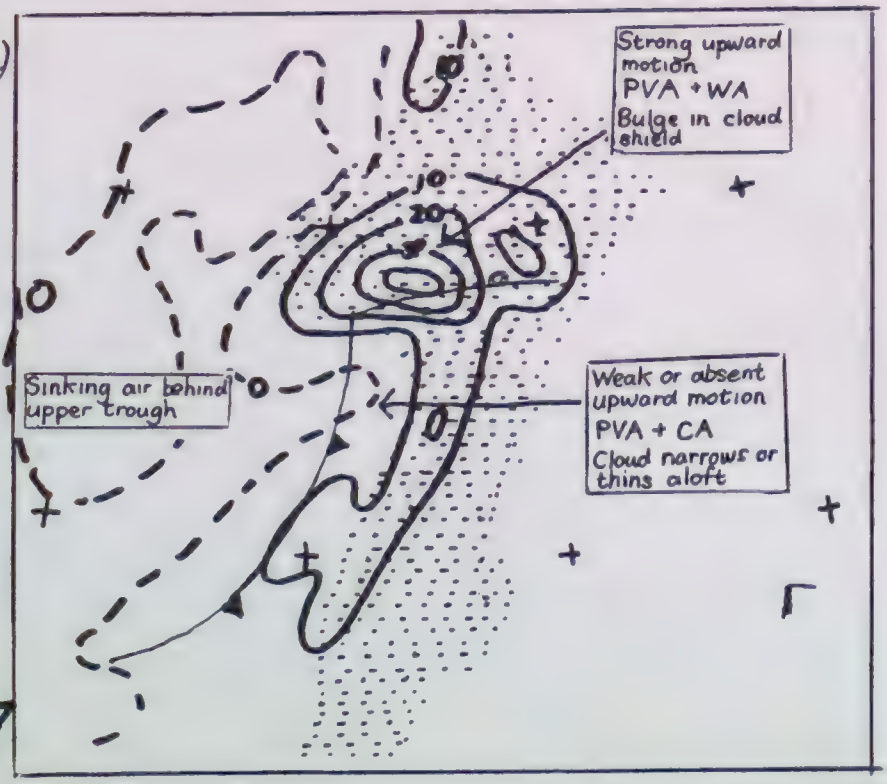
5.3.1.14

(a)

(b)



(c)



09UTC 18/01/88

* **Just ahead of the depression** the contribution to upward motion caused by PVA is augmented by that due to WA causing the following:

- Strong ascending motion concentrated into a relatively small area

- The bulge in the cloud/moisture field where C emerges from beneath F

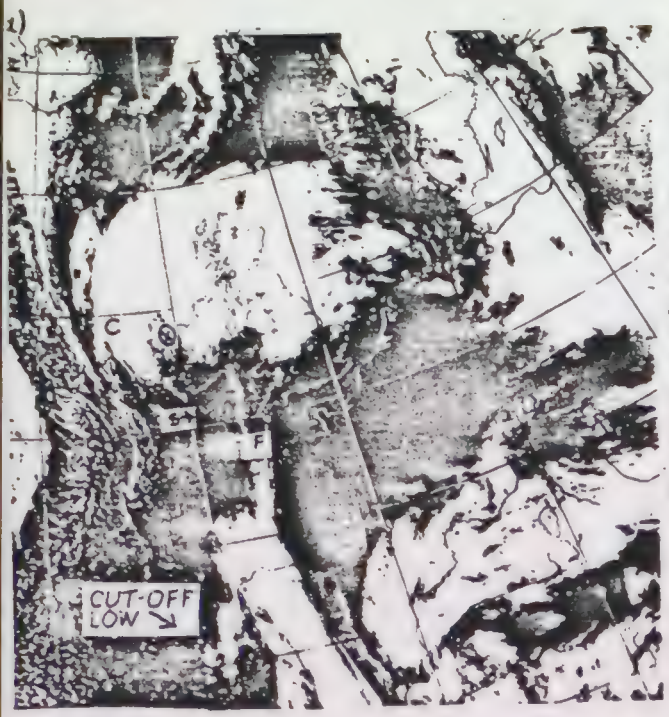
* **Just south of the depression** the effect of CA appears to balance that of PVA. The net results are:

- Suppressed or absent upward motion

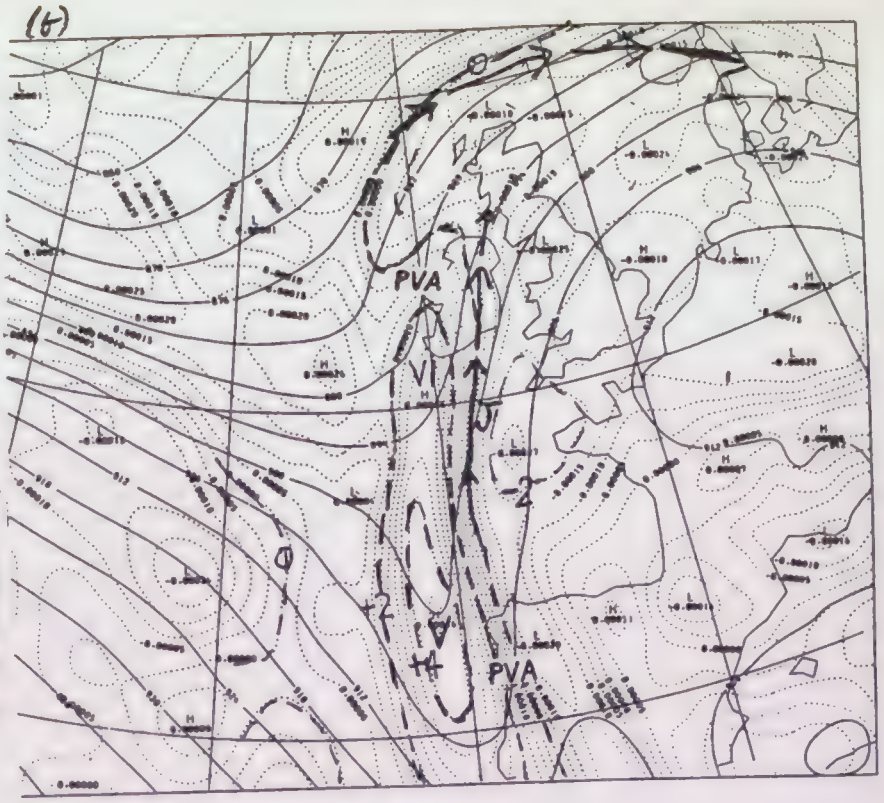
- Upper cloud/moisture starts to dissipate/narrow in this region

Note: The behaviour of the vorticity maximum and its role in cyclogenesis is examined further in another example on ~~p.XXX~~ p.36, exploiting WV imagery and potential vorticity fields

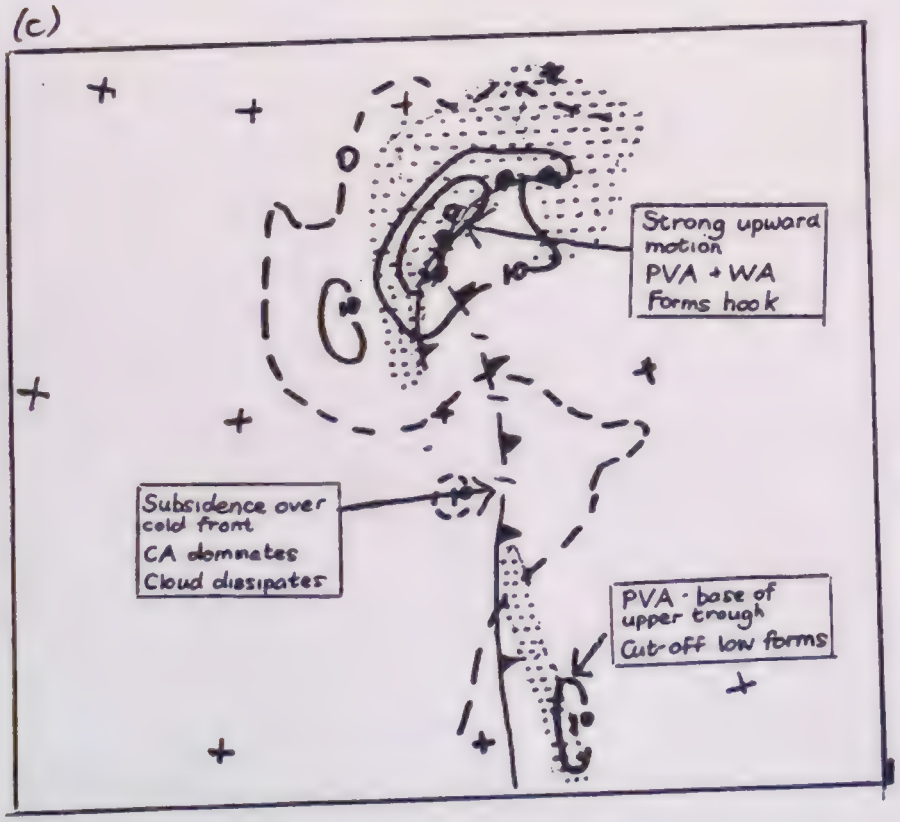
5.31.15



(b)



(c)



03UTC 19/01/88

As evolution continues, a narrow vorticity maximum V1 (located on the cold side of the upstream jet) develops in the rear of the cloud structure; PVA is particularly strong at its forward limit.

* PVA ahead of V1 combined with WA causes the small elongated area of upward motion associated with the distinct hook shape into which C has evolved

* Region of subsidence expands to south of low causing total dissipation of upper level cloud/moisture

* Ahead of V, at the base of the upper trough, strong PVA leads to formation of a cut-off low with its associated cloud signature

KEY: Chart layout

IR image	~ 300mb ht(dam) - - 300mb vorticity (×10⁻⁵) * 400mb RH > 90%
Vertical motion (900-300mb average) -10- mb/hr up -10- mb/hr down (or zero) * 400mb RH > 90%	

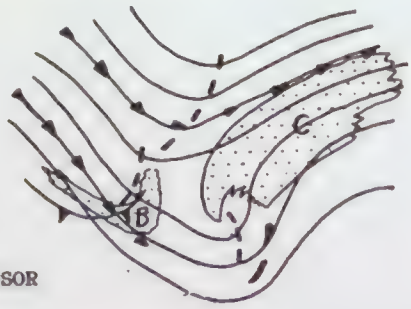
5.3.2. TYPE 2 SPLIT FLOW CYCLOGENESIS

IDEALISED 300MB FLOW AND CLOUD OUTLINE

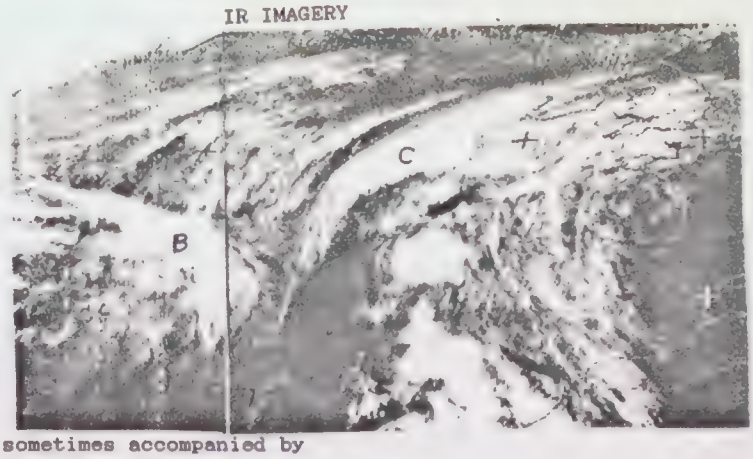
IR IMAGERY

5.3.2.1

(a)



(b)



26/10/89 0900Z

PRECURSOR

* Double jet or split jet

* Short wave moves though the southern jet, sometimes accompanied by cloud feature B

* Thickening, anticyclonically curved cirrus shield C within deformation zone ahead of lower latitude upper trough

* C located north and northwest of where cyclogenesis begins

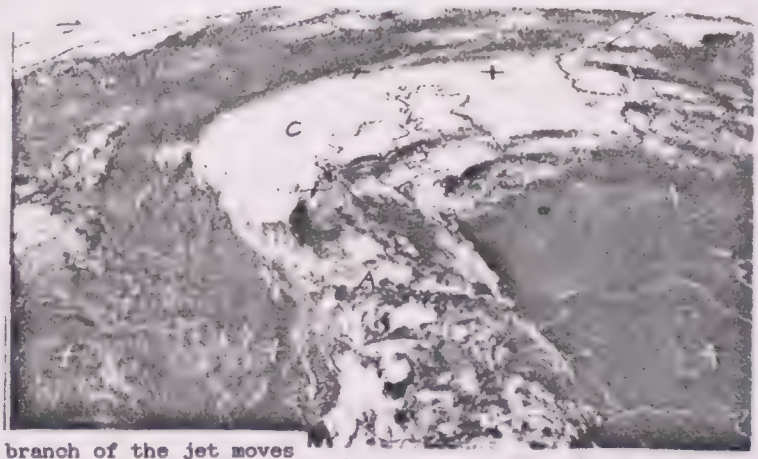
* Mid level convection at southern edge of C

CYCLOGENESIS UNDERWAY

5.3.2.2

(a)

(b)



27/10/89 1200Z

* B develops into a comma as the southern branch of the jet moves around the pre-existing upper trough

In this case, B loses its identity as it rounds the upper trough.

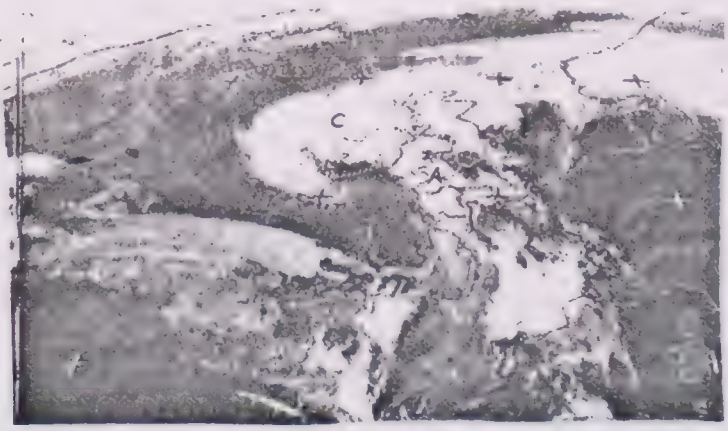
* B often contains much convection

* Cirrus A develops above comma B

5.3.2.3

(a)

(b)



28/10/89 0300Z

MATURING

* Cirrus decks A and C combine to form a large comma-shaped cloud envelope

* Rear edge of upper cloud moves forward of surface cold front, ahead of which lies middle level cloud B; example of a split front

Very poor image sequence (used as stepping) Awaiting better example from US from GSF

NOTES

1. This form of evolution normally relates to the area just east of the Rockies where little low level moisture exists, so there is often no frontal band or "tail" east of the upper trough

2. Rarely seen over oceans

3. Unlike the other archetypes, the upper circulation closes off very early in the life cycle with the surface low reaching maximum intensity at a later stage

5.33 **TYPE 3 CYCLOGENESIS EVENTS**

DISTINGUISHING BETWEEN TYPE 3A (COLD AIR VORTEX / INSTANT OCCLUSION) AND TYPE 3B (INDUCED WAVE) CYCLOGENESIS

Initial upper air pattern: Broad scale rounded upper trough, symmetrical or slightly confluent, with embedded short waves. 2 streams of cloud on satellite imagery - forward frontal band F, and cold air cloud feature(s) C.

Do the imagery and thermal characteristics of C suggest possible cyclogenesis associated with C? See Table 1 - facing page

YES

TYPE 3A

Will the centre of C move to within 350nm of F? (See note)

NO

COLD AIR VORTEX

YES

INSTANT OCCLUSION

NO

TYPE 3B

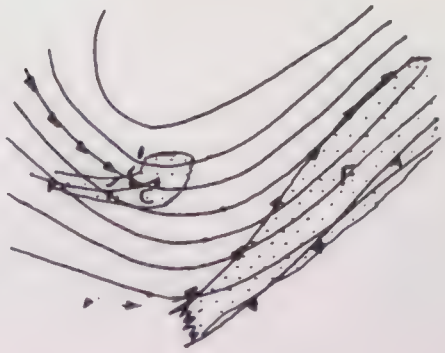
INDUCED WAVE

If C moves to within about 350nm of F, a wave will often be induced on F. This wave will usually be associated with cyclogenesis within F if the upper trough is sufficiently sharp

(* Marshall, 1982)

Note: Satellite image movie-loops and forecast upper air charts are helpful in determining this criterion. Once C and F have come together, the movieloop will also indicate if they are beginning to separate again as occurs if the flow later starts to become diffluent above the system

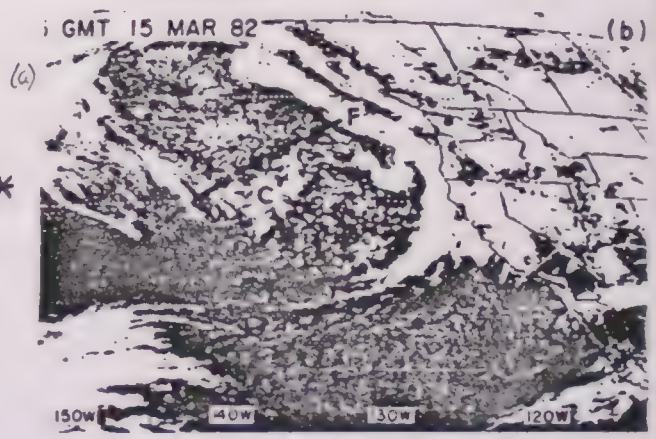
5.3.3.1a

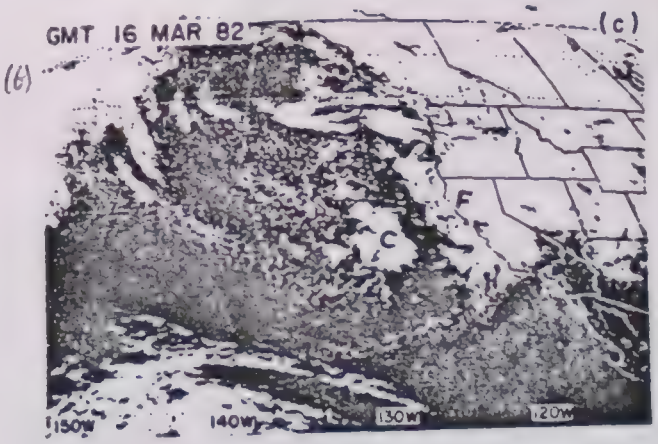


COLD AIR VORTEX

TYPE 3A

5.3.3.2





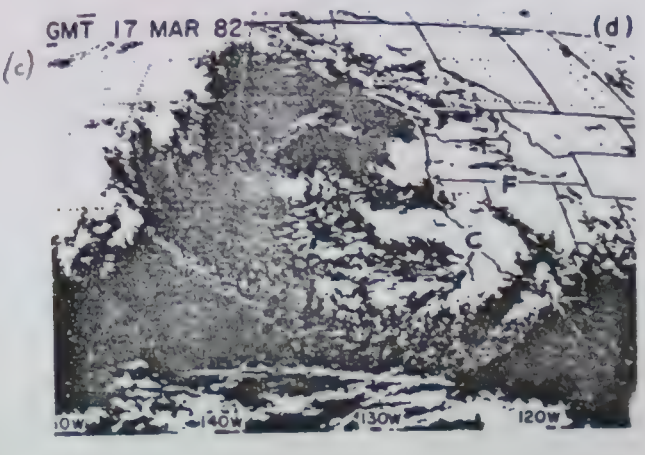


TABLE 1: FACTORS INFLUENCING LIKELY CYCLOGENESIS ASSOCIATED WITH COLD AIR CLOUD FEATURE C

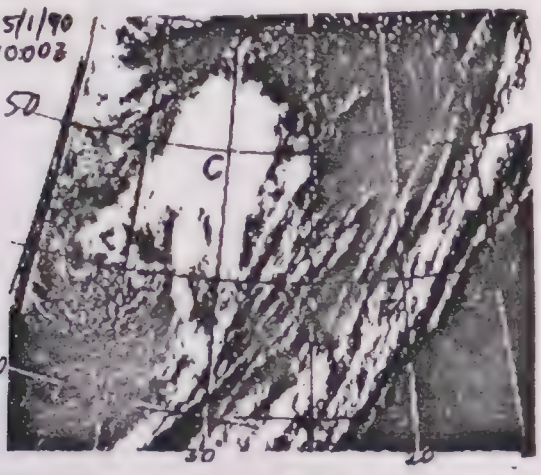
	COLD AIR CYCLOGENESIS FAVOURED TYPE 3A	COLD AIR CYCLOGENESIS NOT FAVOURED TYPE 3B
IMAGERY	C - contains dense layered cloud - consists of several mesoscale cumuliform elements - may be leaf shaped - expanding	C - narrow ragged comma - contains little or no layered cloud - shrinking
THERMAL CHARACTERISTICS	Surface observations or NWP model diagnostics show that a marked thermal gradient accompanies C typically at least 12dam thickness 6C θ_w 4C surface temperature	negligible thermal gradient across C

4

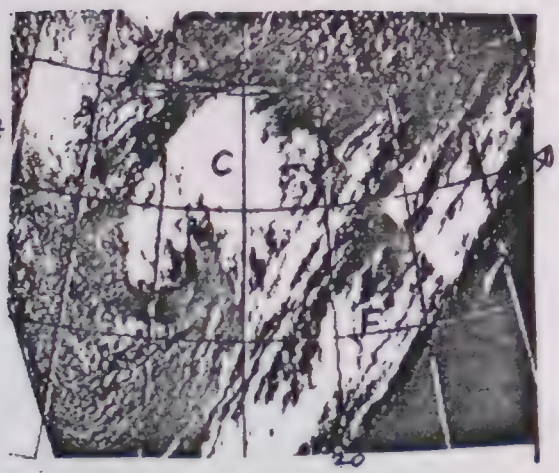
INSTANT OCCLUSION TYPE 3A

5.3.3.3

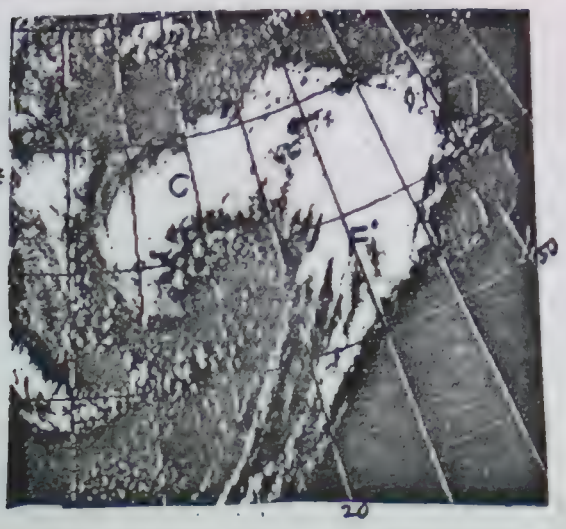
(a) 15/1/90 1000Z



(b) 15:14Z

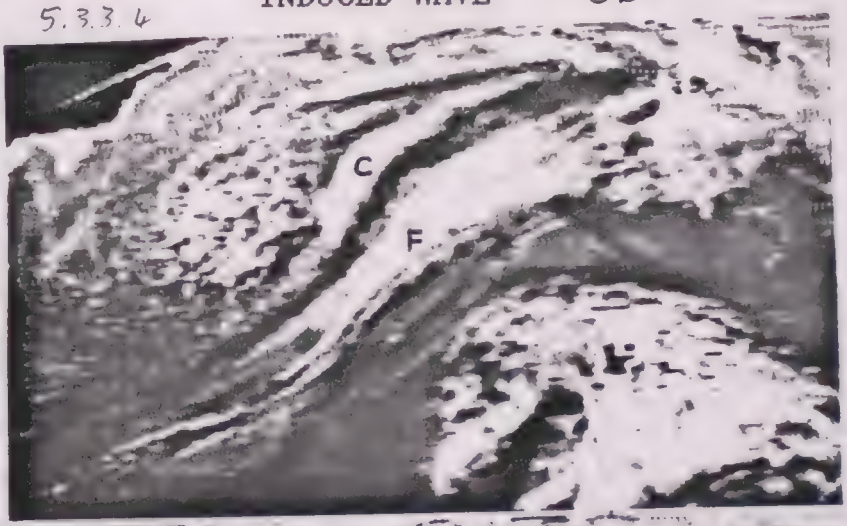


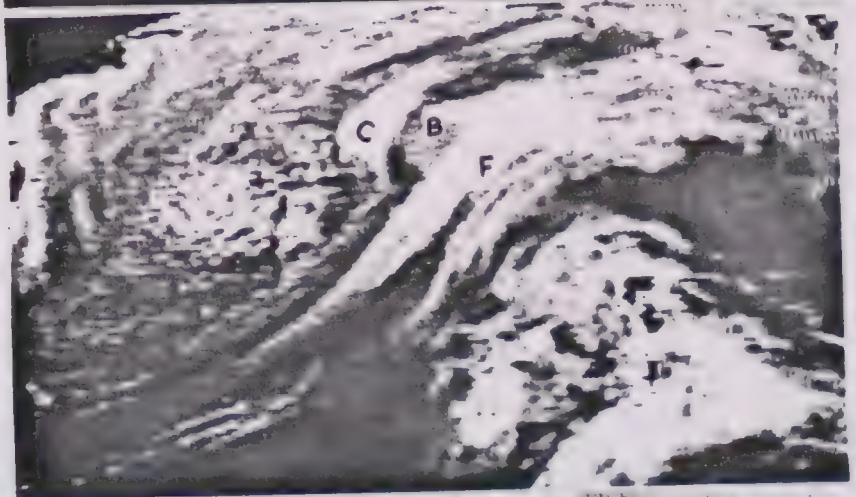
(c) 16/1 03:28Z

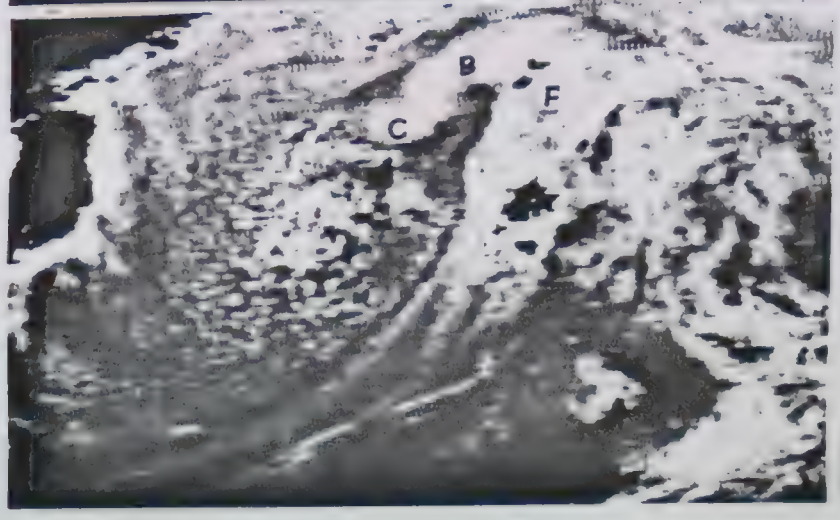


INDUCED WAVE TYPE 3B

5.3.3.4







11

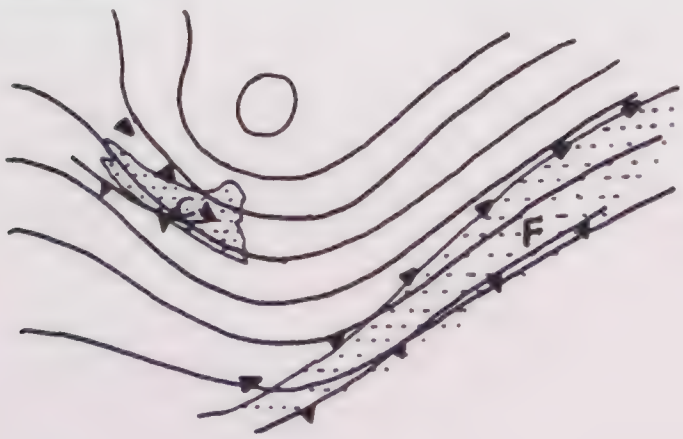
Type (3A)

5.3.3A

COLD AIR VORTEX CYCLOGENESIS

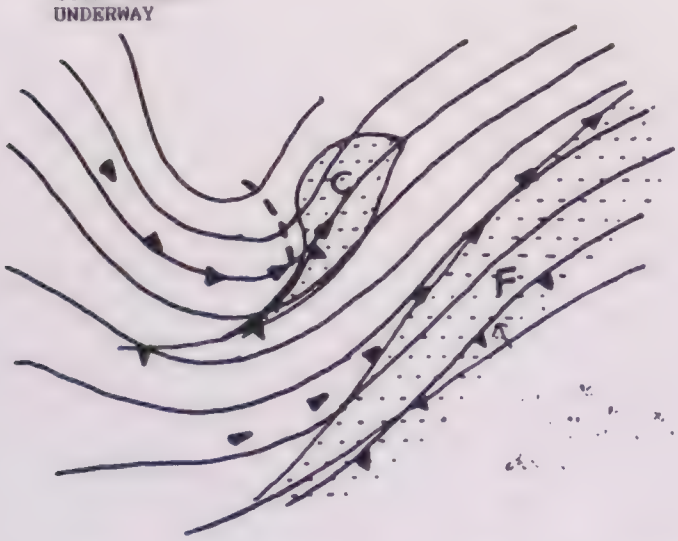
The short wave disturbance that triggers development originates within and moves through the baroclinic zone to the rear of the broad scale upper trough. The short wave remains sufficiently remote from the forward frontal zone to prevent the two features from interacting.

PRECURSOR



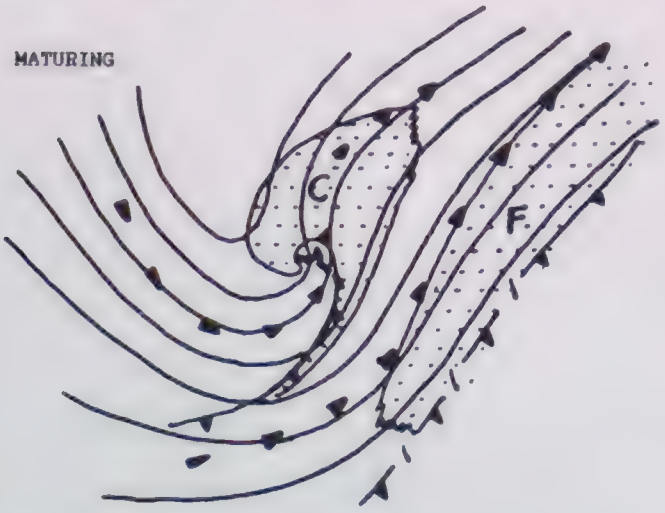
1. Small leaf-shaped cloud area C consisting of mainly low and middle cloud or a mass of enhanced convection. No distinct surface low present yet. Pre-existing frontal band F.

CYCLOGENESIS UNDERWAY



2. As C moves around the major upper trough, it rotates, whilst becoming organised into a comma-shaped cloud envelope. An expanding cirriform outflow moves forward with respect to C. Warmer cloud tops are present towards the tail of C. Probably still an elongated pressure trough at the surface rather than a single low.

MATURING



3. Now that C has formed a distinct hook, a well-defined surface low has developed formed. Warm advection ahead of C weakens F.

IDEALISED 300MB FLOW + CLOUD OUTLINE

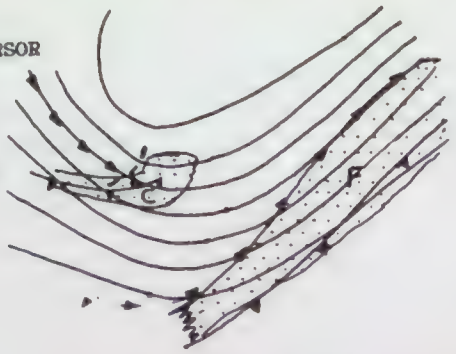
INFRA RED IMAGE

TYPE 3A INSTANT OCCLUSION

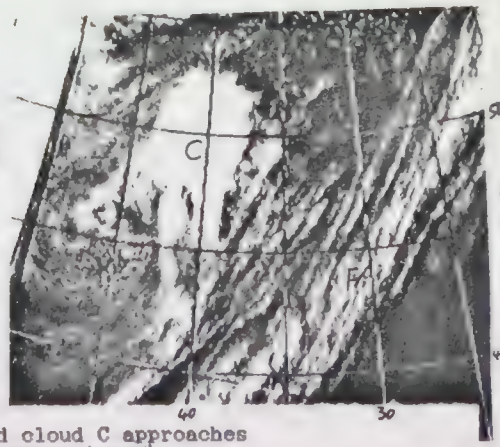
PRECURSOR

STAGE A

5335 (a)



5335 (b)



15/1/90
1002Z

* Expanding area of cumuliform and/or layered cloud C approaches frontal cloudband F which lies ahead of broad upper trough

* C originates upstream of main upper trough and is associated with new jet streak or short wave trough moving through the strong flow

* New convective growth likely on tail of C

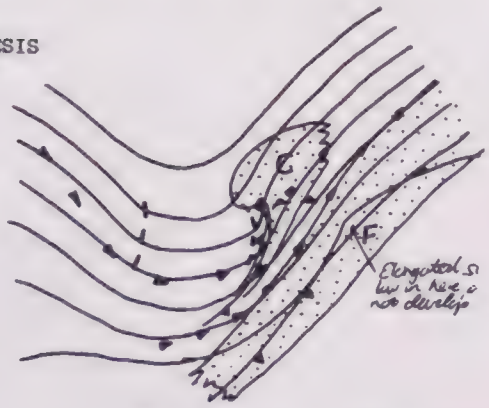
* Sometimes there is just one continuous region of strong flow around the upper trough rather than the two discrete jet axes shown

Key (facing page)
- • Ascent
- o Descent
- ~~ 850mb θ_w
- CA Cold advection
- WA Warm "
- PVA Positive vorticity advection
- NVA Negative " "

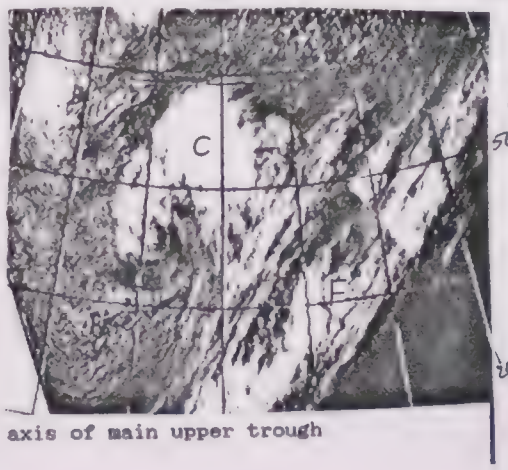
CYCLOGENESIS UNDERWAY

STAGE B

5336 (a)



5336 (b)



15/1/90
1510Z

* C becomes comma-shaped after moving round axis of main upper trough towards F

* Cirriform outflow from C moves forward

* Cloud within tail of C becomes narrower and may dissipate south of jet axis

* The two separate jets (if present) may coalesce, resulting in a very broad region of strong upper flow *(NB there MUST be two jets)*

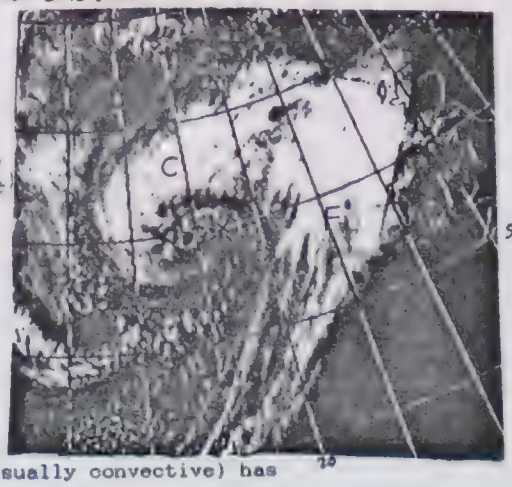
* Minor frontal wave may form beneath F *once C is within 350 nm of F*

MATURING

STAGE C

5337 (a)

5337 (b)



15/1/90
0328Z

* C and F have merged. New cloud growth (usually convective) has filled the gap between the two features

* C evolves into a hook around the surface low, now virtually colocated with the upper level short wave

* Convection occurs along the inside of C

* Upper cloud edge (marking the jet axis) may still separate C and F

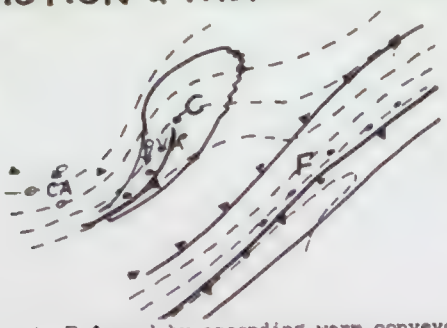
NOTE: NWP FORECASTS OFTEN FAIL TO DEEPEN THE COLD AIR LOW SUFFICIENTLY

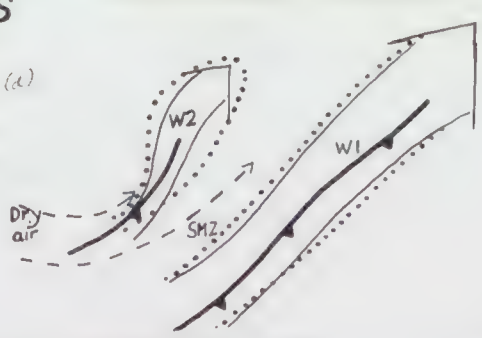
ADVECTION, VERTICAL MOTION & THERMAL FIELDS

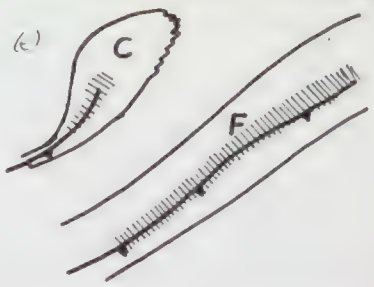
AIRFLOW MODEL

SURFACE ANALYSIS AND PRECIPITATION

5335







* F formed by ascending warm conveyor belt W1 originating in the subtropics ahead of the main upper trough

* C formed by new conveyor belt W2 where air is ascending in a region of PVA ahead of jet streak / short wave trough

* C develops within a secondary region of baroclinicity (seen on e.g. surface obs., 850 θ_w or 1000/500mb thickness) poleward of F

* W2 contains modified polar air originating between C and F. In this region the boundary layer has been warmed and moistened by contact with the sea surface, forming a "shallow moist zone (SMZ)"

* The SMZ between C and F is capped by dry air originating in the region of subsidence (due to NVA/CA) behind F The area is potentially unstable, but convection will normally be suppressed or absent initially.

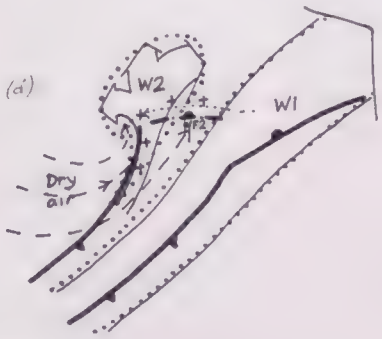
Precipitation related to ascending air in W1 and W2

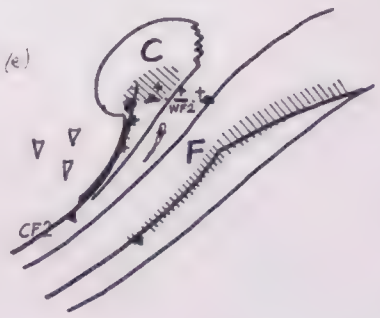
* F - rainfall pattern typical of rearward-sloping ascent

* C - Rainfall often convective

* No distinct surface low beneath C yet; may be a series of troughs rather that one cold front

5336





* Warm air is advected polewards ahead of C, especially at low levels, resulting in

  - a strengthening thermal gradient giving warm frontogenesis at X
  - weakening of low level thermal gradient of F

* Ascending motion in C extends along WF2 where PVA reinforced by WA

* Potential instability is released from W2, particularly as it ascends over new warm front WF2, and new convective cloud grows in this part of the gap between C and F

* A new cold conveyor belt (CCB) (dotted arrow) forms ahead of WF2. It acts as a "cool wedge" over which W2 ascends

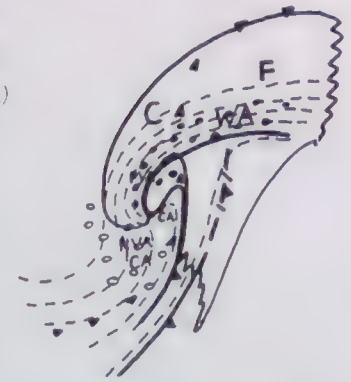
* Precipitation related to W1 and W2

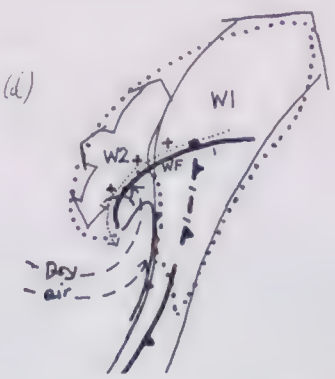
* Heavy rain/thunderstorms likely along CF2 (near low centre) and in vicinity of WF2

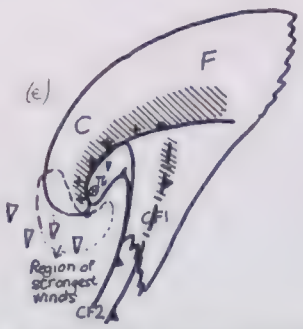
* Low centre forms beneath rear portion of C

* Bands of deep convection may develop in gap between C and F

5337







* Filling of the gap between C and F is completed by cloud formed as W2 ascends over WF

* W2 curves cyclonically around vortex and C becomes hook-shaped. Low cloud associated with CCB emerges from beneath C

* One region of strong thermal gradient now extends around the inside of C, and beneath F.

* Vigorous ascending motion links C and F due to WA beneath F and continued PVA beneath C

* Warm air may become secluded over the depression centre

* Heaviest rain accompanies the strongly ascending air around inside of C, where W2 ascends over the frontal region. Mid-level convection likely here

* CF1: rainfall usually weakens. CF2: small amounts of rain, but it introduces the cold air

* CF1 and CF2 together resemble a split front (see Ch 4). CF1 is the upper front, whilst CF2 is a surface front

* Surface low located beneath dry slot; showers and thunderstorms may form quickly here

TYPE 3A EXAMPLE OF IMAGERY + DIAGNOSTICS (BROADSCALE)
INSTANT OCCLUSION

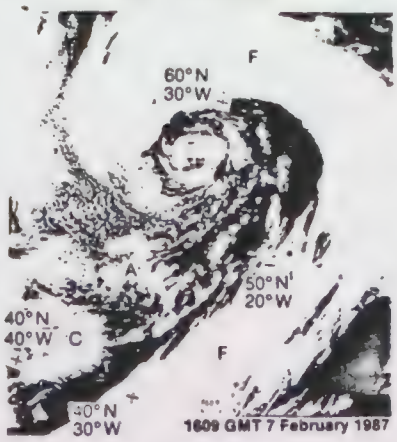
SATELLITE IMAGERY

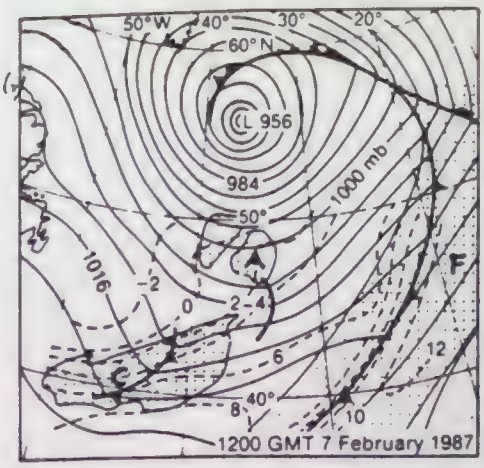
This example illustrates many aspects of the evolution shown in the schematic figures (pp 13-14)

IR IMAGE

PMSL, CLOUD OUTLINES
850MB θw

5.3.3. 8 (a)

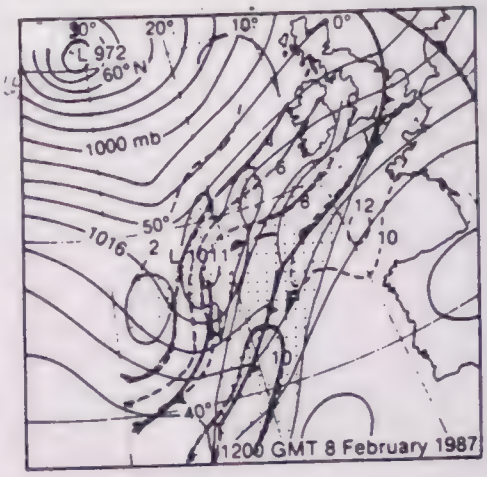




Points worthy of note are as follows:

* In this case there are two cloud clusters A and C poleward of F. Both are associated with ascending motion and are moving around the periphery of a broad, rounded upper trough, towards F (Figs 8(a)-(d))

5.3.3. 9 (a)



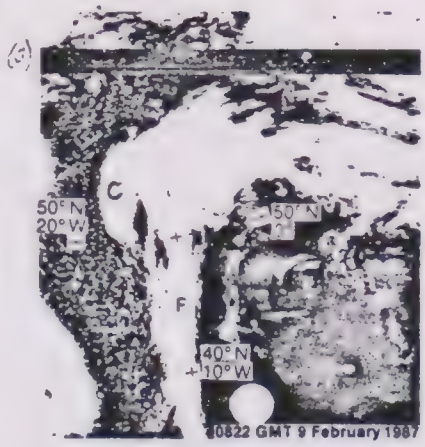
* The filling of the gap between C and F by new cloud growth G. This region is characterised by

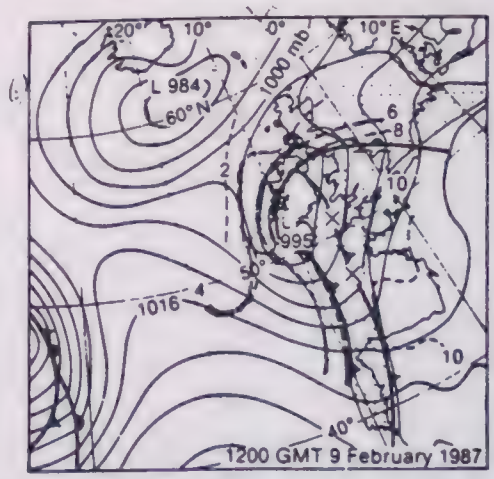
- strongly ascending air in a region X extending across from C to F (Fig. 9(d))

- formation of a strong 850mb θw gradient and warm frontogenesis (Fig. 9(b))

* The thermal gradient across F weakens markedly, and the rearward cold front now marks the transition to cold air (Fig. 9(b))

5.3.3. 10 (a)

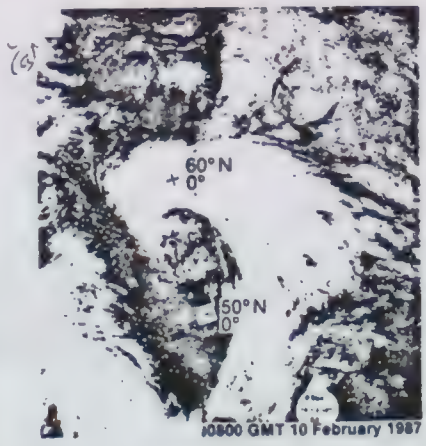


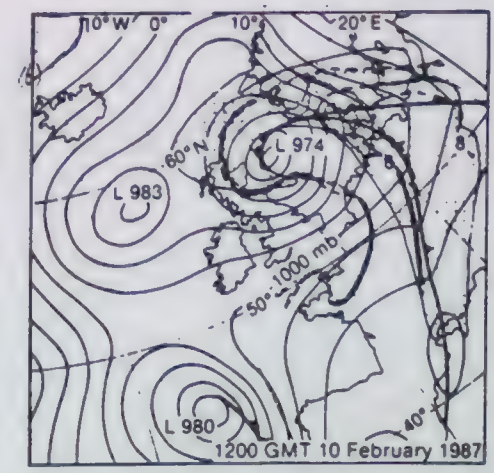


* C has evolved into a well-marked hook. A strong thermal gradient extends around the inside of the hook (Fig. 10(b))

* F begins to dissipate upwind of C in region of subsidence (Figs 10(b), (d))

5.3.3. 11 (a)



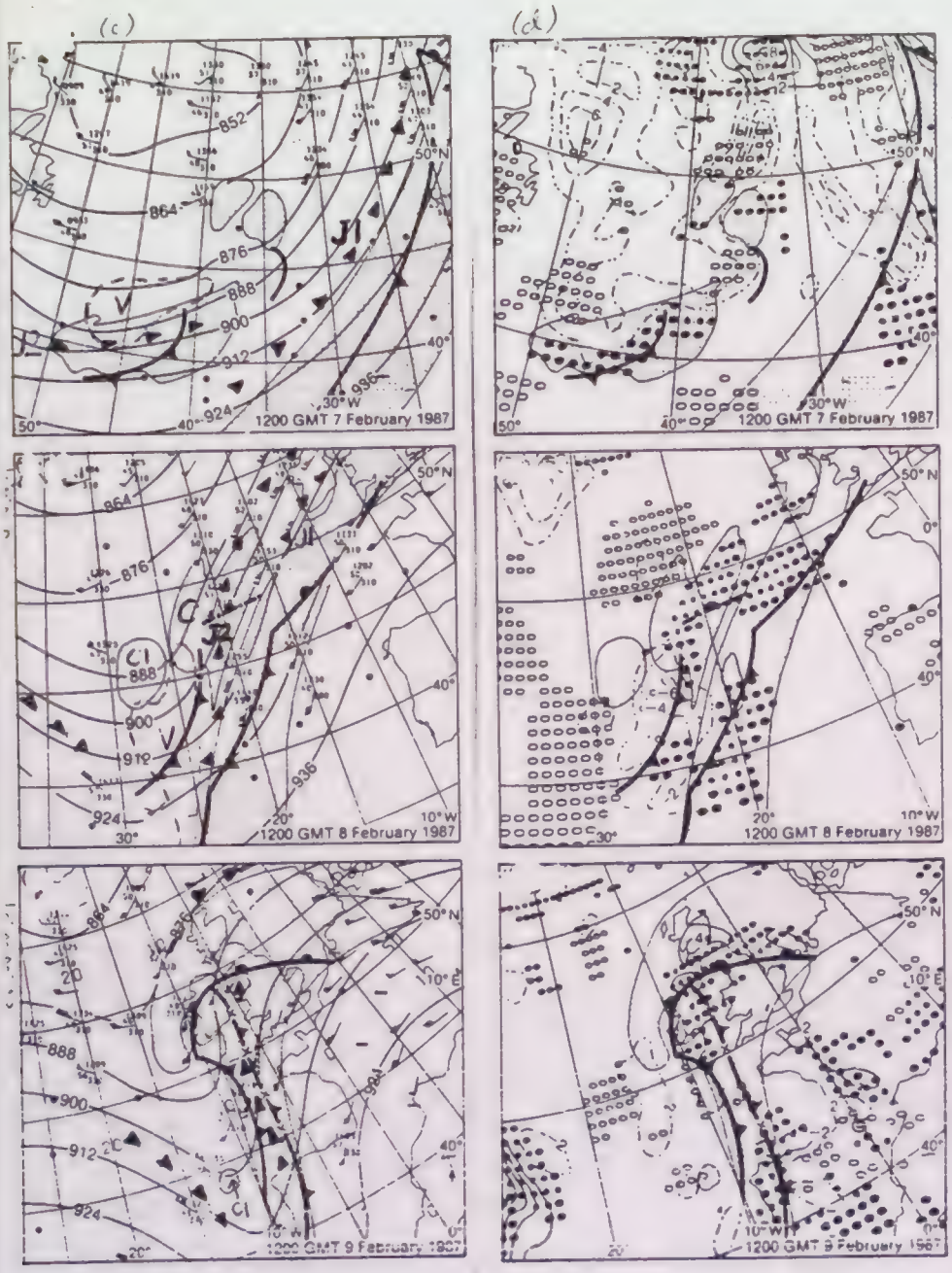


* A new depression forms several degrees east of the cold air low (originating from the forward extension of the elongated low pressure in Fig. 11(b)) This new low deepened rapidly to become the vigorous circulation centred east of Scotland (Fig 11(b))

300MB HEIGHT, + JETS
CLOUD OUTLINES

5338

VERTICAL MOTION AND
ADVECTION FIELDS +
CLOUD OUTLINES



DIAGNOSTICS

* C and A lie ahead of short wave troughs embedded in strong flow [8(c)]

* Ascending motion in both features caused by PVA - note the large vorticity maximum V immediately upwind of C in Fig. 8(c)

* The jet J2 associated with C has moved around the forward side of the upper trough and virtually absorbed J1 (Figs 8(c), 9(c))

* Area of ascending motion accompanying C expands and extends along the new warm frontal zone. C still lies in region of strong PVA downwind of V (Fig. 9(c))

* Strong cold advection becomes established behind C (Fig. 9(d))

* Strong ascending motion exists in the region of marked WA ahead of the warm front and along the inner edge of the hook and dry slot (Fig. 10(d)) This ascent led to rapid formation of showers and thunderstorms in the dry slot soon after the time of the image

To identify which of C and A is likely to be the main focus of cyclogenesis, note that

* C covers a larger area than A and contains much layered cloud as well as convection (Fig. 8(a))

* C possesses a stronger thermal gradient than A (Fig. 8(b))

* The ascent/descent couplet accompanying C is much larger than A (Fig. 8(d))

Provided these characteristics remain, then C is likely to be associated with the major cyclogenesis rather than A

Differences from the schematic model

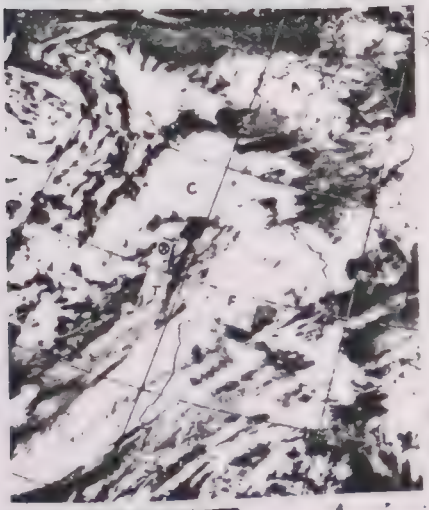
* On the forward side of the extending upper trough, a wave was carried eastwards towards Iberia, embedded in the large area of ascent W (Fig. 9(d)), along with the remains of cumuliform cloud area C1, situated at the base of the trough.

* Deepening is usually almost complete by the time merging of C and F occurs. On this occasion renewed rapid deepening occurred following this stage

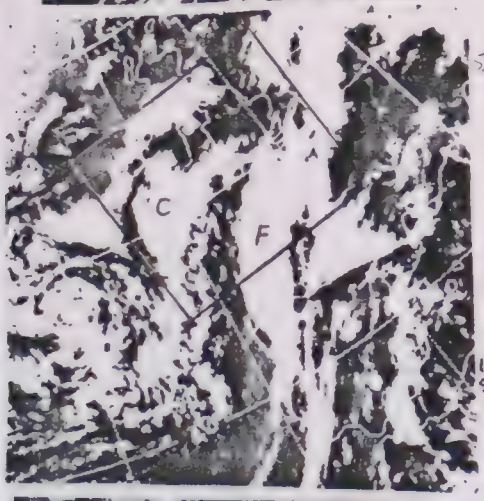
EXAMPLE OF TYPE 3A - INTRODUCING MESOSCALE WEATHER DISTRIBUTION

This case shows a good example of how cloud features on the imagery relate to surface analysis and weather during a Type 3A instant occlusion event. This case is chosen because the key events (e.g. filling of the gap between C and F) occurred over a data rich area, where observational coverage was further enhanced by data from the FRONTS87 project

0511Z 5/1/88

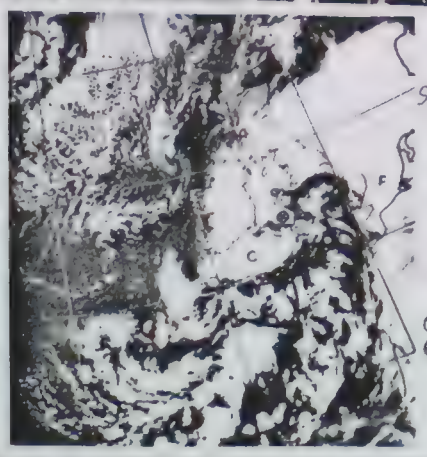


1500Z 5/1/88

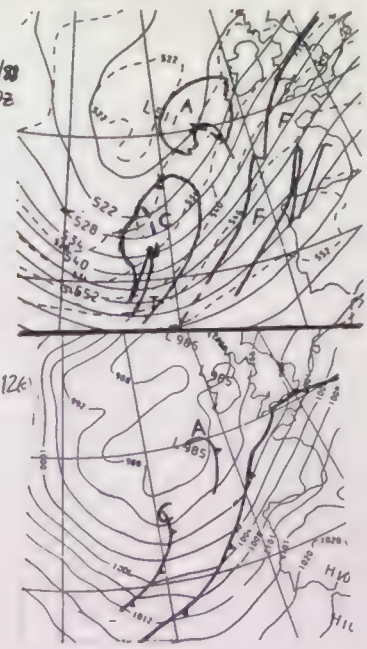


The box is the area of Fig. 5.3.3.16

1800Z 5/1/88



0600Z 6/1/88



SYNOPTIC-SCALE CONTEXT

* Clumps of cloud C and A are present on the cold side of frontal band F. Both are as yet associated with ill-defined surface lows - see note

* The comma-shaped cloud area C, which is moving towards F, consists of a series of mesoscale convective elements as well as cirriform outflow

* Tail T of comma C probably corresponds to a cold front

* T becomes less well-defined and breaks up altogether as the area between C and F is overrun by dry air aloft (see WV images)

* Convection is initially absent between C and F (for the reasons given on p14).

* New bands of convective cloud grow ahead of the remnants of T. Such convection fills the gap between C and F between the times of the last two images. This process is shown in more detail on the next page

* C eventually evolves into a hook which moves around the depression centre

Note:

Initially, two areas of cloud A and C are present in a baroclinic zone on the poleward side of F (as on 7/2/87 case). To identify which (if any) would be associated with the major cyclogenesis note that

* C is developing close behind A and thereby preventing cold advection from becoming established behind A (see 500mb - 1000/500 thickness chart)

* C is larger than A and lies ahead of the extending upper trough

The implication is that C is likely to be the major system, with the upper flow carrying it towards F

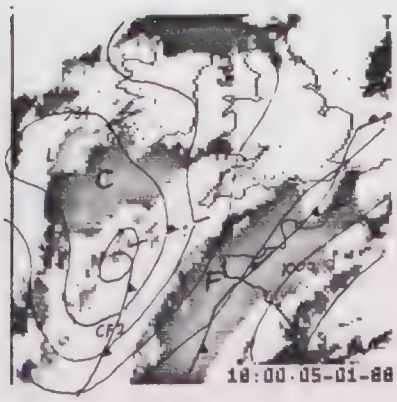
Differences from archetype :

C is apparently joined to F at an early stage by middle level cloud that is very conspicuous on IR images. This cloud was, however, thin and was not associated with precipitation, in contrast to the convection that developed later on.

MESOSCALE WEATHER DISTRIBUTION

The images below focus on important changes that took place to the cloud pattern between the times of the final two IR images in the sequence on the previous page. This corresponds to evolution from stage **B** to **C** of the schematic sequence ~~(pXXX)~~ (pp 13-14).

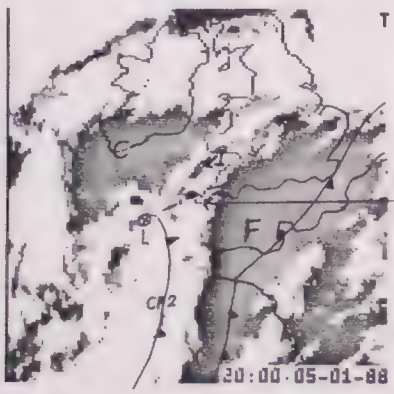
Colour sking
Black <-40 c
Red -30 - -40
White > -30



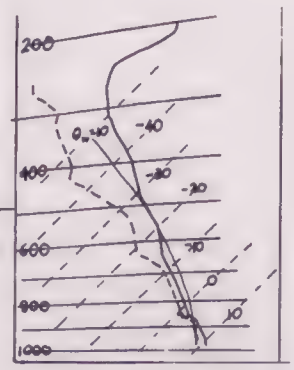
* C and F are very well marked and correspond to ascending conveyor belts W2 and W1 respectively.

* Dry air aloft has overrun CF2 and the low level warm moist air within W2 on its forward side, generating considerable potential instability in the lower troposphere (see Camborne radiosonde ascent 21GMT 5/1/88).

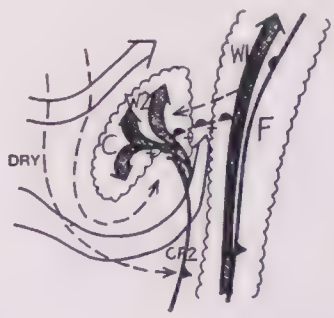
* CF2 lies along one of several new convective bands that are forming between C and F

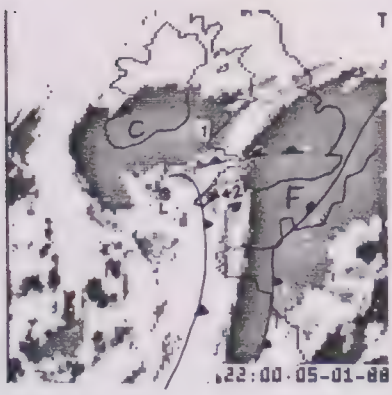


5.3.3.17 (a)



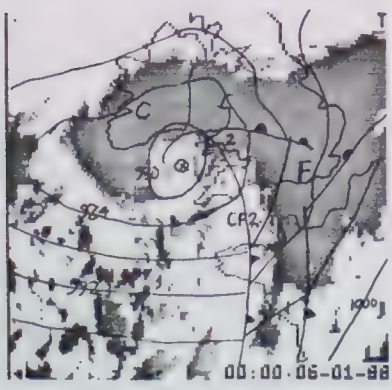
5.3.3.17 (b)



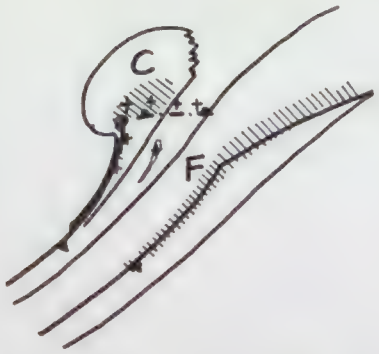


* Convection which develops just ahead of CF2 grows very rapidly where W2 ascends over the new warm front (see airflow model). Two such pockets of convection are identified - labelled 1 and 2. Area 2 contains thunderstorms and effectively seals the gap between C and F.

* An elongated and well developed depression centre already exists at the inner edge of C at 18GMT 5/1/88. Centre begins to become clearly defined on imagery at 22GMT with the formation of a hook



* Widespread deep convective cloud in cold airmass behind CF2



5.3.3.18

(a)

(b)

French radar missing 00GMT

PRECIPITATION DISTRIBUTION AND SURFACE ANALYSIS

The following pair of COST73 images demonstrate the relationship between the cloud and rainfall. The following features are worthy of note:

* Rainband beneath F associated with conveyor belt W1

* Heavy rain is associated with conveyor belt W2 i.e.

- Narrow band of heavy convective rain along CF2, and extending around the inner edge of hook C (part of which is beyond radar coverage).

- Rainfall on CF2 is confined to the region close to the depression centre, north of the jet axis, where strong ascending motion is taking place within a potentially unstable environment

- Heavy rain (and thunderstorms) from new cloud growth that bridged the gap between C and F. Rainfall also extends eastwards ahead of the new warm front

Surface features

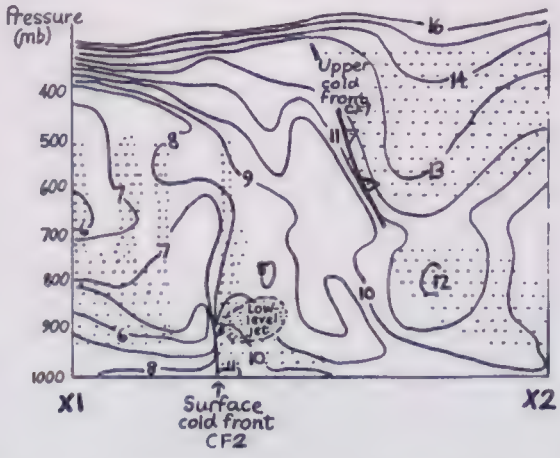
The surface observations plotted on the images demonstrate the following features very clearly

WF2 - warm frontogenetic zone forward of the cold air cyclogenesis

CF2 - marks the transition to cold air at the surface. The strongest surface winds (40-50kn mean speeds in this case) followed soon after the passage of this front (base of hook).

The inner front (consisting of CF1 and WF1) which although difficult to identify at the surface, was still well-marked aloft (see cross section)

5.3.3.19 VERTICAL STRUCTURE



Cross section along line X1-X2 of 00GMT 6/1/88 image. θ_w isopleths are continuous lines and stippled areas are cloud and/or 80% relative humidity.

CF1 and CF2 together resemble a split front (see Ch 4)

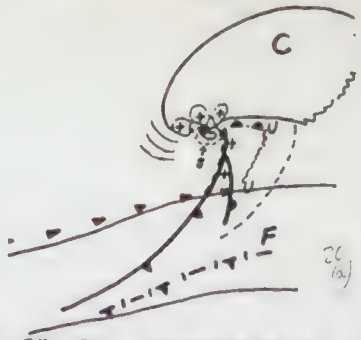
* CF1 is the upper front - a well marked middle and upper level moisture and θ_w boundary

* CF2 is the surface front - preceded by a low-level jet (dense stippled region) and accompanied by a sharp drop in θ_w

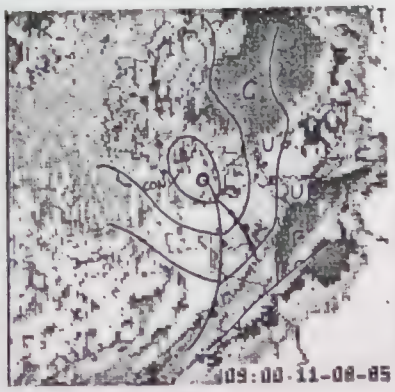
Example of Stage B

A common cloud configuration seen for a time during various forms of cyclogenesis (notably types 3A, 4A and 4B) is two adjacent cloud areas C and F, separated by a wide gap

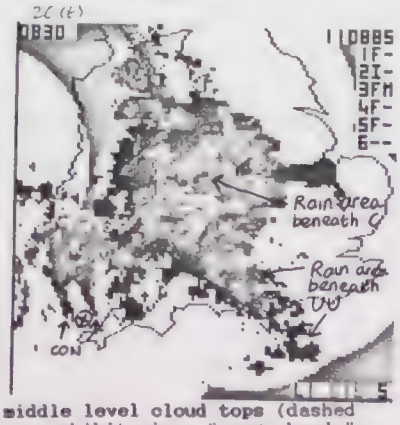
* The gap between C and F usually ranges from 120-300nm and is most prominent on IR and WV imagery due to the presence of dry air aloft poleward of the jet axis. F will sometimes be thin or narrow (as in the following example) and its northern limit is defined by plumes of cirrus moving along the jet axis

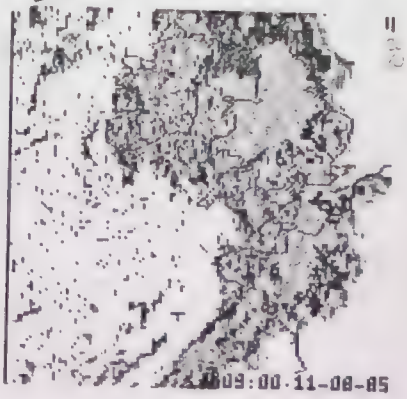


IR IMAGES



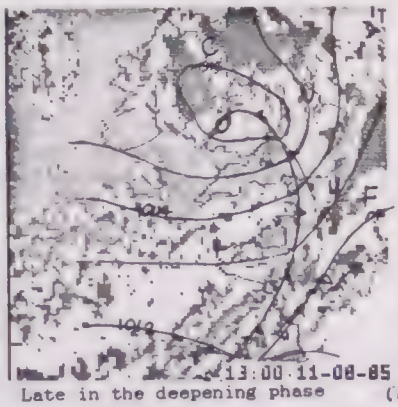
RADAR

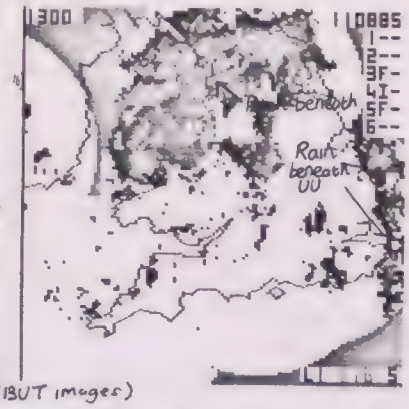




* C and F will be connected by low to middle level cloud tops (dashed outline on the schematic figure) which may exhibit minor "surge bands" UU. (Surge bands; cross-reference Ch. 4) The rear edge of the cloudband will be most prominent on VIS imagery

* A surface front (often analysed as an occlusion) lies along the rear edge of the low to mid level cloud band.





* Late in the deepening phase (13UT images)

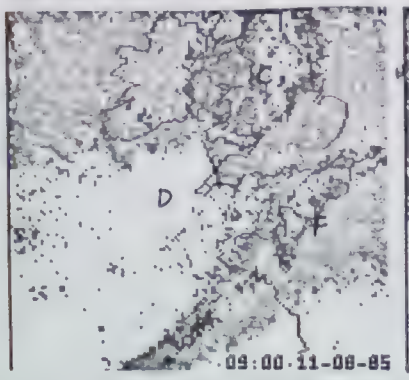
- Rapid growth and cooling of cloud tops associated with the surge band UU will often occur, resulting in new cloud (labelled X on 13UT IR image) linking C and F. This will form the occlusion cloudband of the mature system

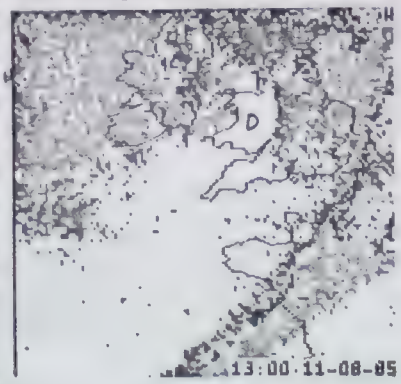
- Deep convection may form along or just ahead of the surface front north of the jet axis

The following additional aspects of ~~about~~ the surface analysis are worthy of note:

* The images at 09UTC provide a very good example of how the deepening low centre lies near rapidly growing convection cells (e.g. labelled "CON"), and that the cells "radiate" from its location. In this case the hook that forms around the centre at 13UT results from the coalescence of these convection cells

* There are two preferred locations for warm fronts (see Fig 20d) - one at the leading edge of a narrow tongue of warm air ahead of the cold front, and the other a warm frontogenetic zone along the southern limit of C





Precipitation

* Much of the precipitation is related to ascending warm conveyor belt W2. A narrow band of rain may also be associated with W1

* Heaviest rain beneath the inner portion of C beneath the strongest gradient of cloud top temperatures. Thunderstorms are very likely when mid-level convection is present

* New rainfall growth likely beneath surge bands

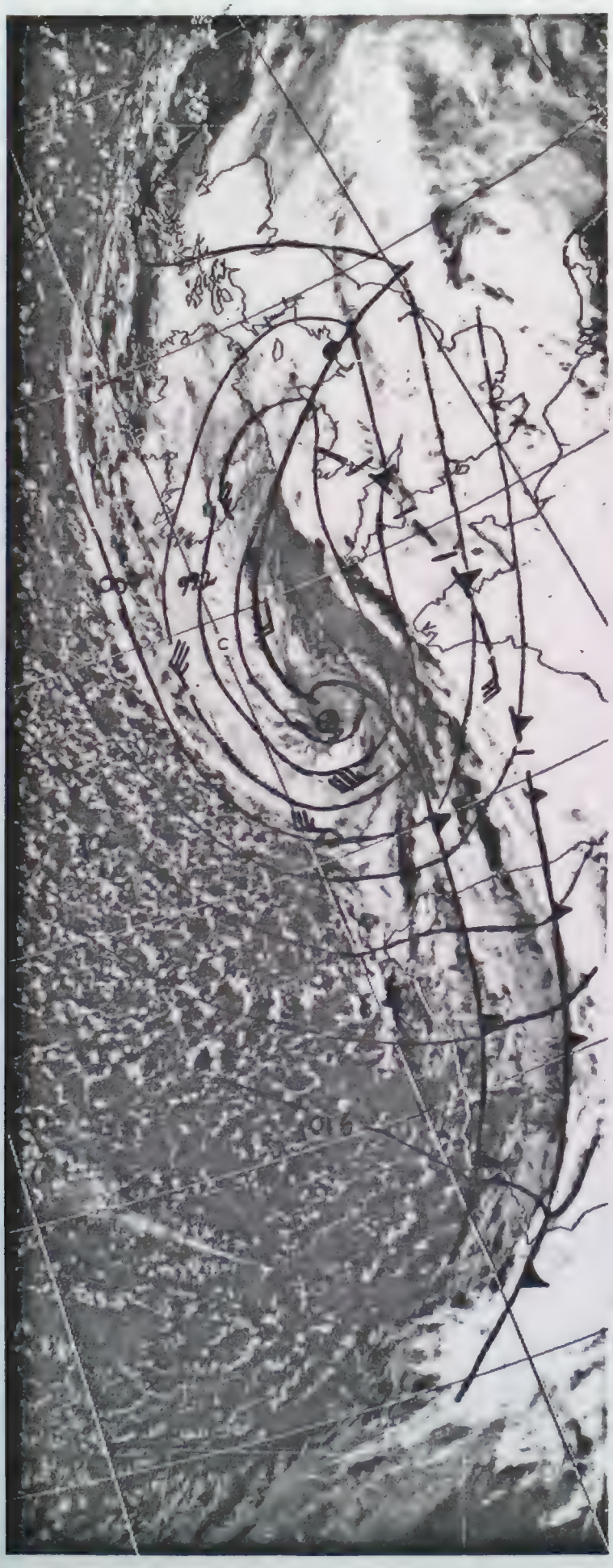
WV images

* A narrow band of dry air aloft separates C and F

* A pre-existing upper level dry tongue, D, enters the rear of the cloud system during rapid deepening to form the very prominent dry slot on the 13UT image

EXAMPLE OF STAGE C OF INSTANT OCCLUSION

This case shows a good example of how cloud features on imagery relate to surface analysis and weather during the final stage of the instant occlusion i.e. after the two component cloud features C and F on the schematic, have coalesced. Two images are shown, primarily to highlight the growth of deep convection in the dry slot.



09GMT 08/12/86

* Cloud area C has evolved into an elongated hook - a well marked cloud free slot separates C and F

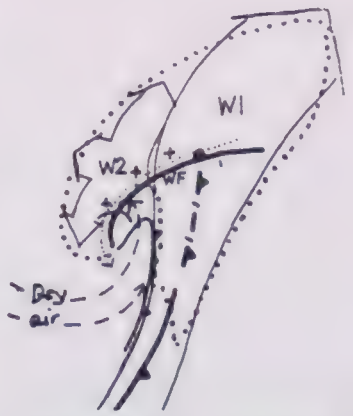
* An elongated, complex depression lies along the inside edge of C. A vigorous vortex is located within a small swirl of cloud at the tip of the hook

* **The strongest surface winds** (up to 60kn in this case) **are located at the base of the hook**, lying immediately behind CF2

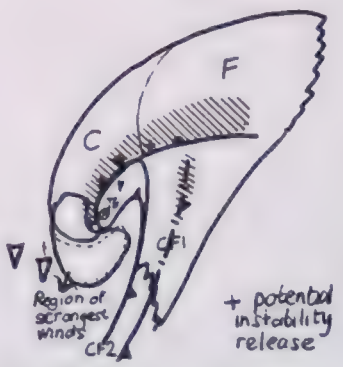
* F corresponds to ascending conveyor belt W1; C corresponds to W2

* Pockets of mid-level convection occur on inside edge of C where W2 ascends over the sharp frontal zone WF2

* Cold cloud tops H have almost advanced onto the forward side of the low therefore deepening is virtually complete.



AIRFLOW MODEL (b)



(c) SURFACE ANALYSIS & PRECIPITATION (HATCHED)

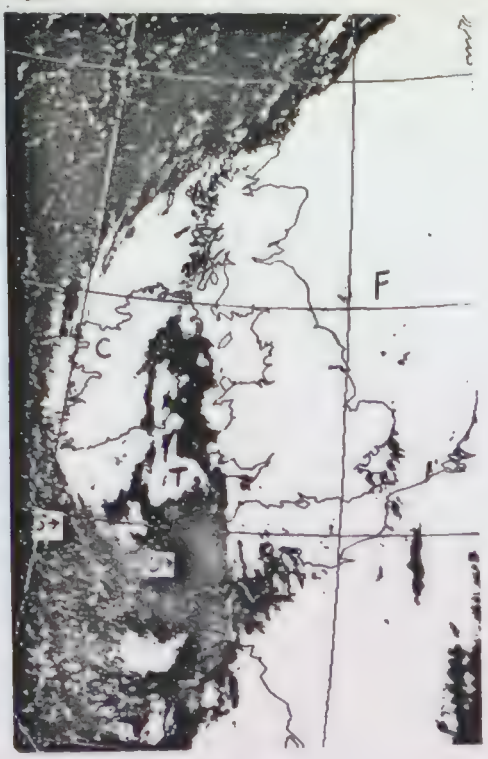
5 3.3.23

(a)
NOAA-10
0927z
8/12/86

15GMT 08/12/86

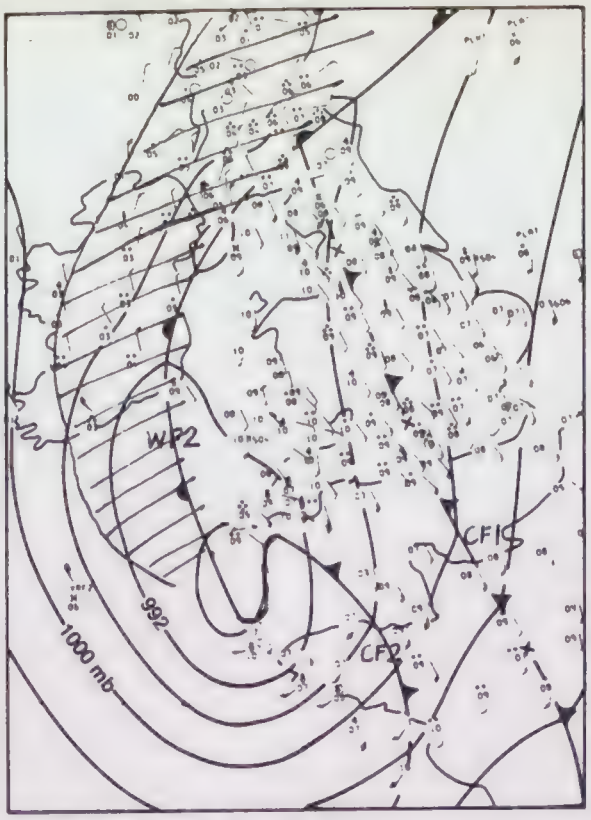
533.26

(a)



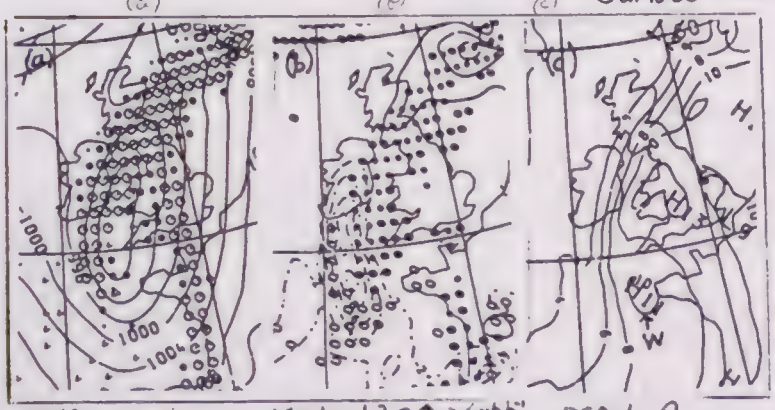
IR image

(b)



Surface PMSL, wind, dewpoint, weather

(a) (b) (c)



PMSL + rain

Vertical velocity } ● ↑ >6mbh⁻¹ ○ ↓ >12mbh⁻¹

Thermal advection } ~ Warm τ(6h)⁻¹ -- Cold τ(6h)⁻¹

850mb θ_w

* The NWP model diagnostic charts (left) have been selected since they correspond well with the observed surface weather and analysis. They are derived from a forecast, data time 12GMT 07/12/86

* **Deep convection (labelled T) has grown within the cloud free slot** - due to strong upward motion immediately ahead of the depression centre (inset (b)). This case also demonstrates how the convection sometimes develops at the forward limit of the swirl of low cloud that has moved around the depression centre

* The band of rain that extends along the inside edge of C and beneath F is colocated with strong ascending motion over the region of pronounced thermal gradient (insets (b) and (c)) associated with WF2

Surface analysis

* CF1 ill-defined in terms of thermal contrast. It possesses a rainband, but this weakens; note how the region of ascending motion accompanying the rainband is fragmented

* CF2 gives small amounts of rain but introduces colder air with lower dewpoint

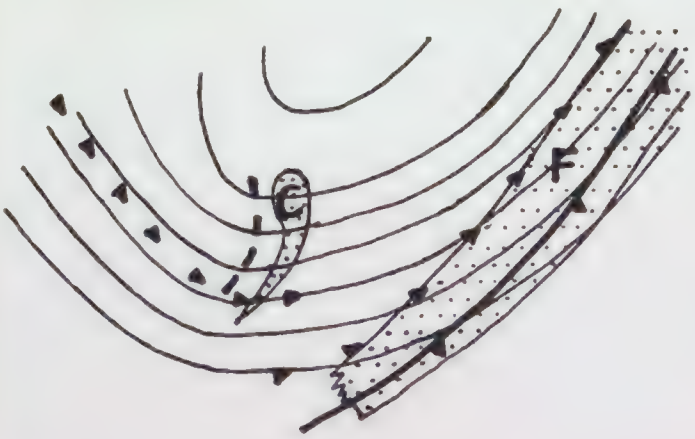
* Warm air appears to have been secluded close to the depression centre; note the small isolated region of high θ_w air labelled W on inset (c). (Comparison of the image and analysis suggests that the secluded air corresponds to the very small cloud free region D) on IR image

* Another indication of strong surface winds is narrow streets of shallow convection (labelled S) immediately behind C

Note: In this case CF2 coincides with the leading edge of the low cloud which has emerged from beneath C, and circulated around the depression centre in the strong low-level flow. This is effectively the cold conveyor belt (dotted arrow on airflow model), consisting of moist, rain-cooled air originating ahead of WF2

TYPE (3B) INDUCED WAVE CYCLOGENESIS

5.3.3.26(a)



PRECURSOR

* Broad, rounded upper trough; embedded short wave(s) upstream

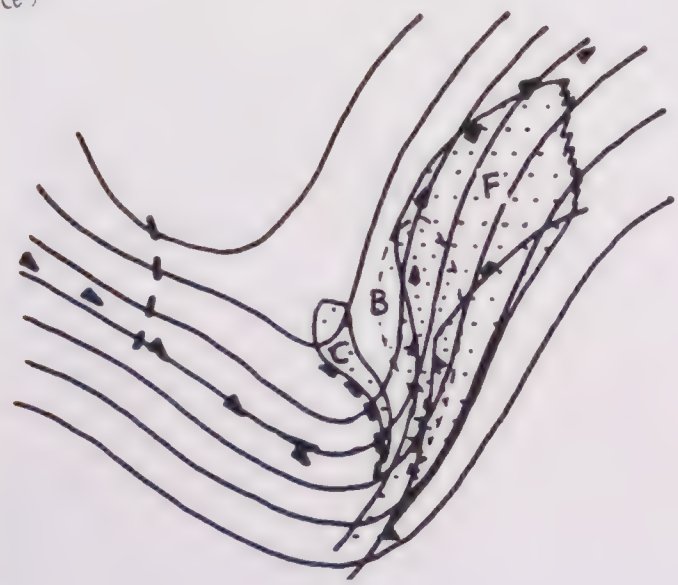
* Band of frontal cloud F ahead of trough

* Comma shaped cloud feature C ahead of short wave, often ragged and narrow

* C possesses little thermal gradient either at surface or aloft

* Stronger thermal gradient beneath F

(b)



CYCLOGENESIS UNDERWAY

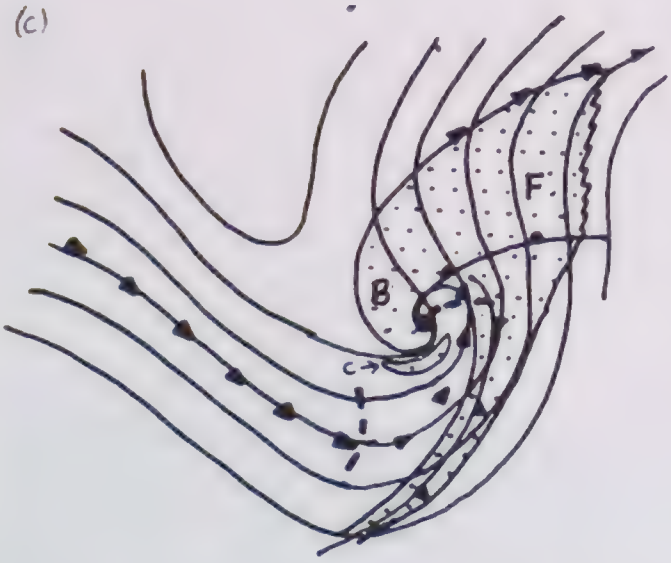
* A wave forms on F resulting in the characteristic S-shaped rear edge as C approaches to within about 350nm

* New middle level cloud B appears on poleward side of F - signals that cyclogenesis has already commenced beneath F

* B either emerges from beneath F or is revealed as the rear edge of F (the surge region) accelerates forward

* C usually begins to shrink

(c)



MATURING

* B forms a hook around the surface low; by now well-developed

* The fragmenting remnants of C are carried into the circulation of the vortex, and usually merge with B

The cloud pattern during cyclogenesis is very similar to Type 1 except for the added presence of the convective comma. For overview of airflow models and analysis and weather see Type 1 on p 1-2

In Type 3B, the trigger for cyclogenesis, namely the short wave trough, is evident on imagery due to presence of comma C. By contrast, in Type 1 there is often no pre-existing signal on imagery of the short wave trigger

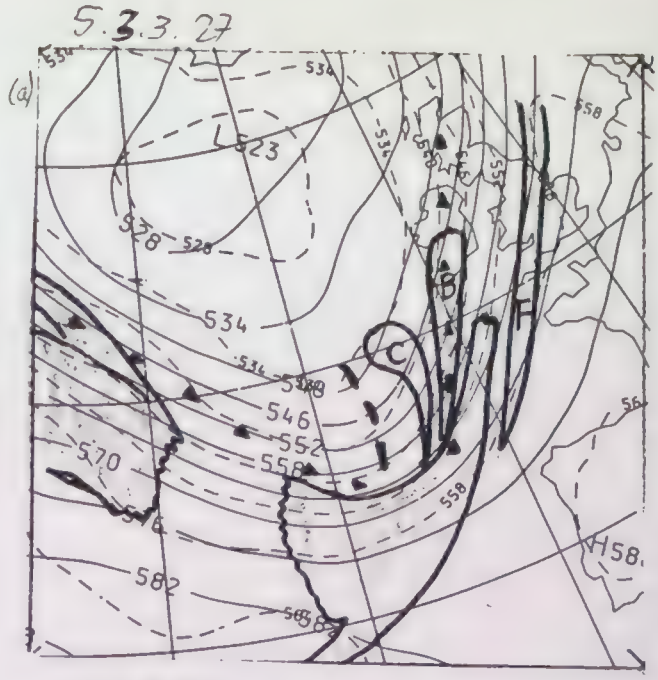
(a) Precursor 15GMT 9/6/86

* Pre-existing frontal cloudband F

* Convective comma-shaped cloud formation C approaches F from upstream. C lies in a region of strong PVA ahead of a short-wave trough immediately north of the jet axis, and posesses a surface trough

* Upper cloud growth B takes place to the rear of the frontal cloudband adjacent to comma C. This is the first warning of cyclogenesis

* The major low-level thermal gradient (represented by 850mb WBPT- dashed lines on surface chart) is concentrated on the forward front as opposed to the cold air feature C



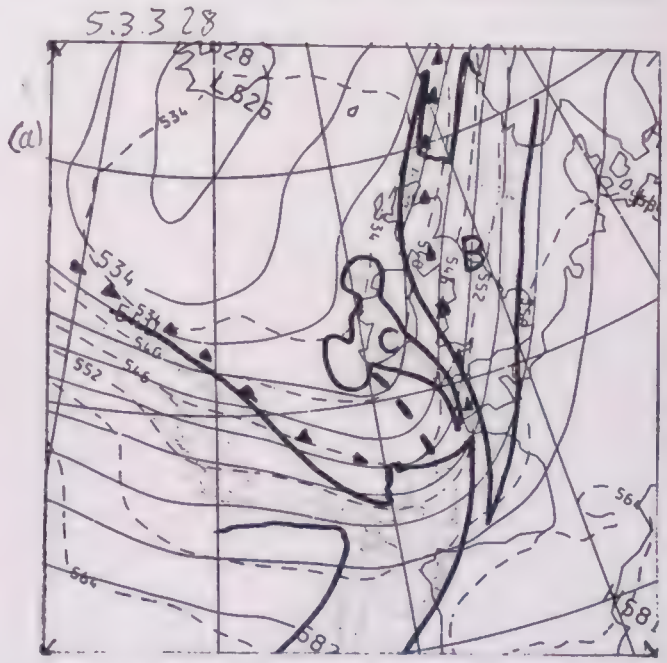
03GMT 10/6/86

(b) Onset of more rapid deepening

* Cloud area B grows considerably and develops an S-shaped rear edge - symptomatic of incipient cyclogenesis

* C remains in phase with B and itself has a minor circulation at 52N 10W

* The major low-level thermal gradient remains associated with the forward front. Therefore the inference is that further cyclogenesis will occur on this forward front rather than the cold air feature

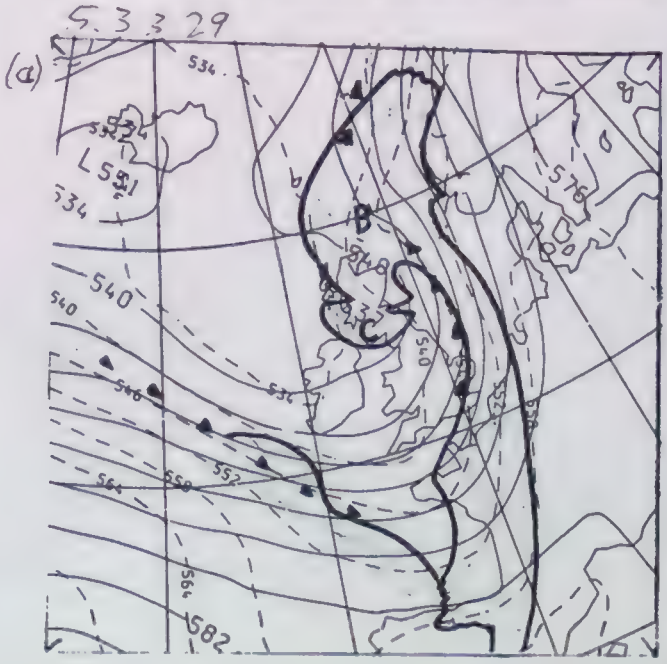


15GMT 10/6/86

(c)

* Cyclogenesis is well underway, a distinct hook/dry slot having formed.

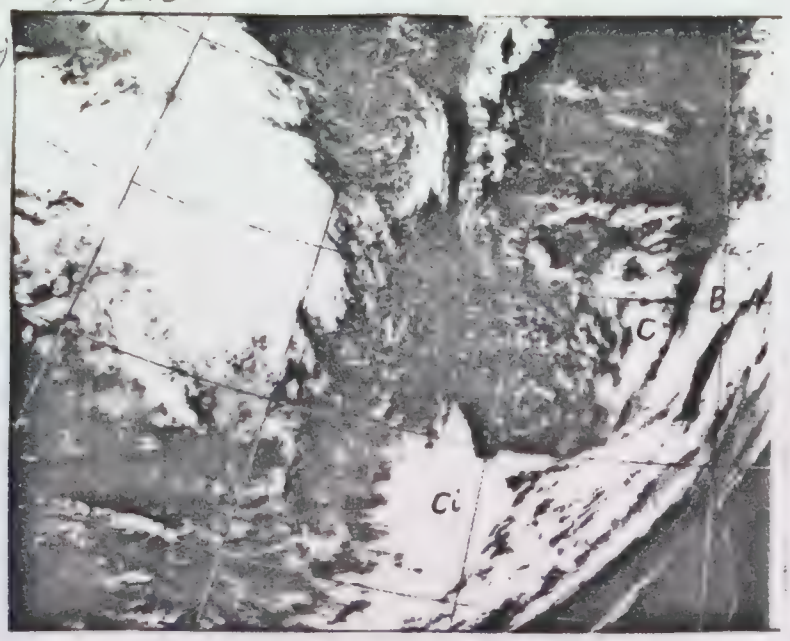
* Cold air cloud feature C becomes absorbed into the circulation of the deepening forward depression



More details of stages (b) and (c) are given on pp. 26-27.

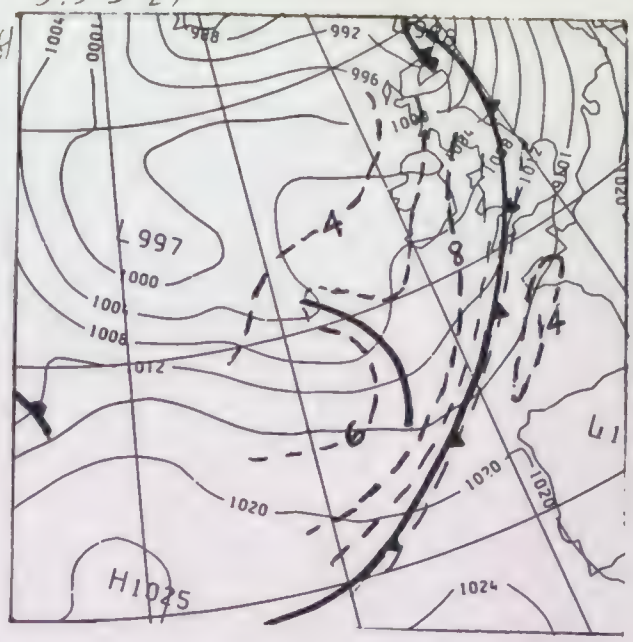
5.3.3.27

(b)



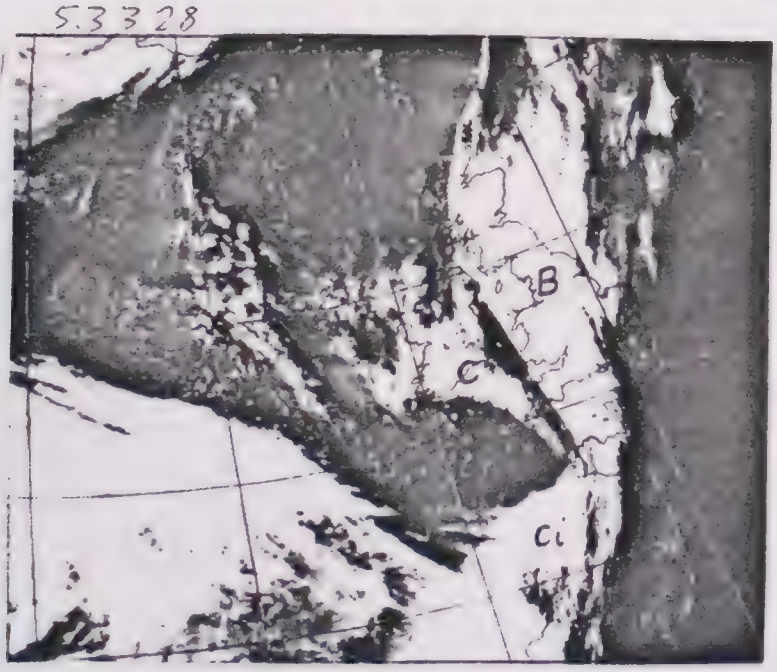
5.3.3.27

(b)



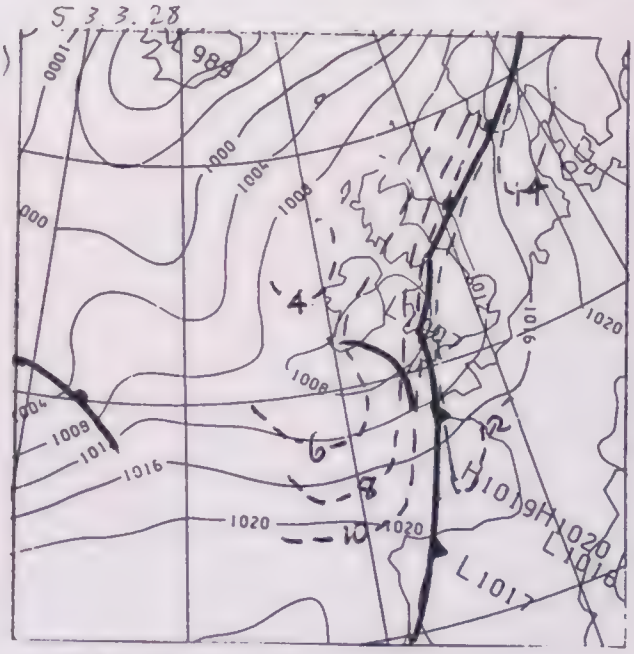
5.3.3.28

(b)



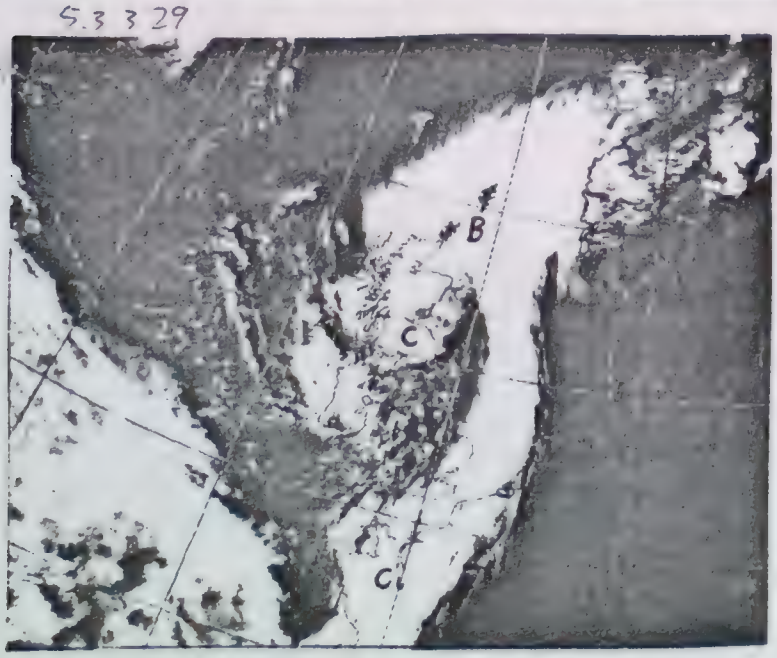
5.3.3.28

(c)



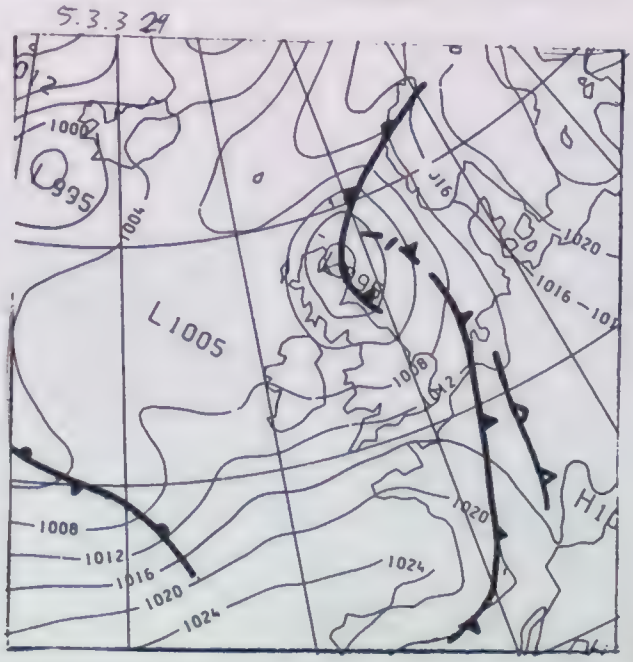
5.3.3.29

(b)



5.3.3.29

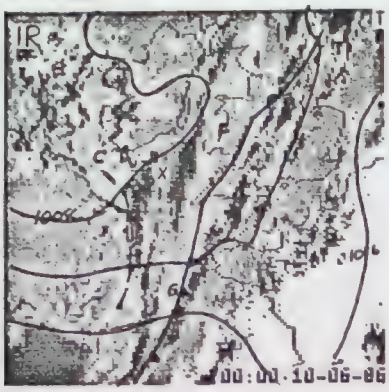
(c)



TYPE 3B EXAMPLE OF MESOSCALE WEATHER AND ANALYSIS 10/06/86

The Meteosat images presented below demonstrate mesoscale aspects of the interaction between short wave cloud feature C and frontal band F which culminate in a Type 3B (Induced wave) cyclogenesis

5.3.3.3(a)



* F develops an S-shaped rear edge adjacent to C

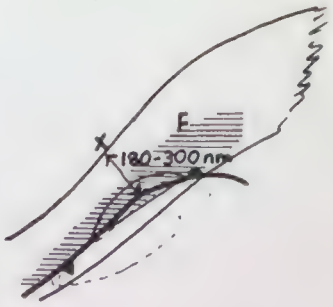
To locate the centre of gravity (CG) of the surface lows beneath F: Apply the rules for Type 1, Stage 1 (p.xxxx), illustrated in the schematic inset. (5.1, p.13),

First note that since **F is narrow** (less than 240nm wide) recall the exception to the rules for Type 1, namely:

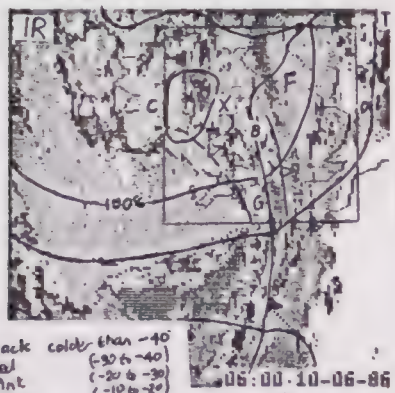
* We relax the criterion that the centre lies 180-300nm in from the inflection point X (since this would locate the centre outside the cloudband of F!)

* Instead place the CG in the **middle of F** adjacent to inflection point X (in this case over SW Britain). Note that there is at present at least one transient centre

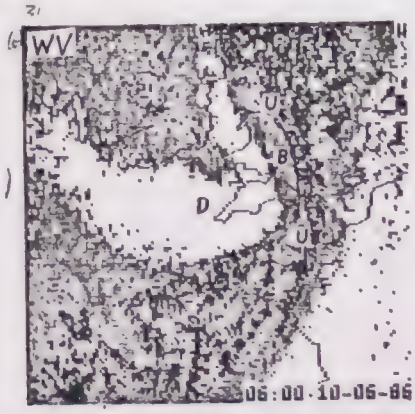
3.0(b)



5.3.3.3(a)

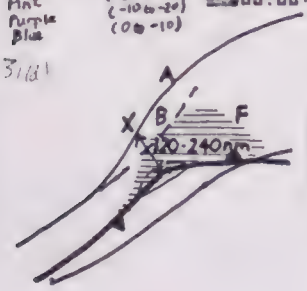


Black cold: than -40
Red (-30 to -40)
Pink (-20 to -30)
Purple (-10 to -20)
Blue (0 to -10)



Covers the boxed area on Fig 3.1(a)

3.1(b)



* As the wave on F develops, the leading edge of dry air aloft, UU, surges forward revealing mid-level cloud tops - region B (see Note)

To locate the centre of gravity (CG) of the surface lows beneath F: Since surge has moved forward revealing mid-level cloud B, apply the rules for Type 1, Stage 2 (p.xxxx), illustrated in the schematic inset.

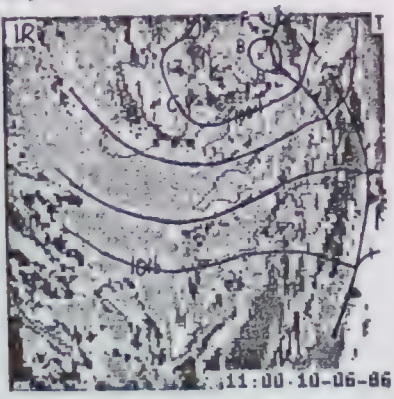
Note again that F is narrow (less than 240nm wide). Therefore place the CG in the **middle of F** adjacent to inflection point X at rear of B (in this case over northern England).

* A narrow band of convective rain lies along the tail C

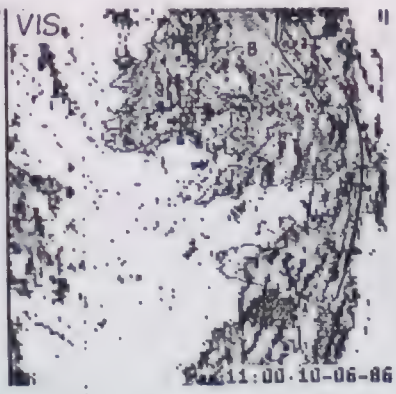
* Separate bands of heavy rain are concentrated along the surface and upper fronts

* Analysis differs slightly from inset. Surface cold front lies towards the rear edge of B; similar to split-front, with UU as upper cold front - see radar image.

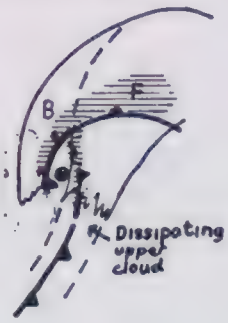
5.3.3.3(c)



3.2(b)



The heavy rain is on the inner edge of B, beneath the brightest cloud.



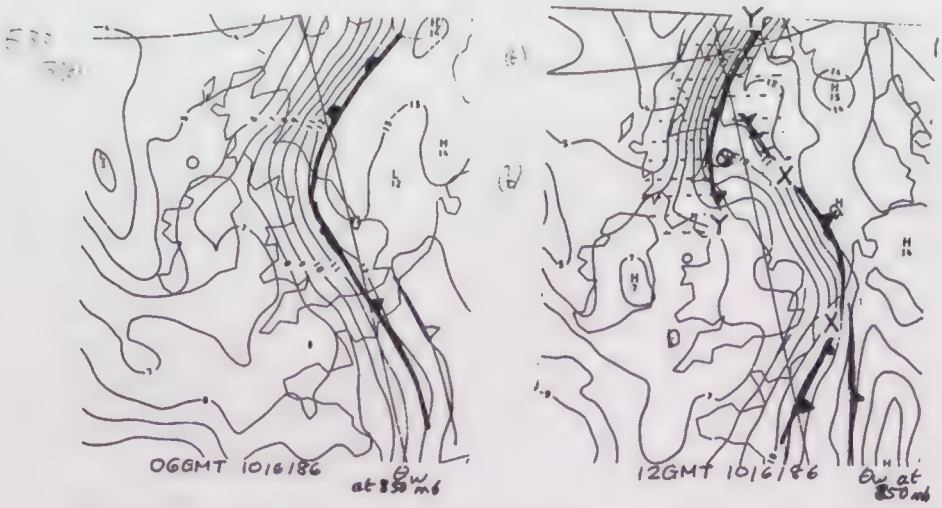
* Mid level cloud B evolves into a hook as a dry slot forms (very prominent on VIS image)

* Complex low centres deepen and consolidate beneath dry slot

* C swings rapidly round into the circulation of the depression; C shrinks and becomes disorganised (most noticeable on VIS image)

NOTE: The schematic insets have been reproduced from Type 1 (p.xxxx) but have been relabelled. The letter B is now used (instead of C) to identify the new mid level cloud tops

This example also provides a clear illustration of how the thermal fields evolve during transtion from a simple wave to a developing cyclone with a dry slot. It illustrates one of the frontal evolutions shown in the Introduction on p.8 of section 5.0.



The thermal gradient that is initially continuous on the cold side of the front (Fig. (a)) becomes "fractured" near the depression centre (Fig. (b)). This arises since

* The portion of the gradient XX, associated with the cold front moves forward followed by strong cold advection

* The thermal gradient becomes concentrated (i.e. frontogenesis) along YY, north and west of the depression, along the inner edge of the hook. Part of this forms the bent-back warm front

* Between these two regions, the thermal gradient becomes diffuse i.e. frontolysis occurs. Corresponds to region of the dry slot on imagery

By comparing Figs. (a) and (b) with 06 and 11UTC images respectively, it is seen that negligible thermal gradient accompanies C

5.3.3
34

Schematic representation of frontal evolution related to the cloud pattern for this case

5.3.3
35

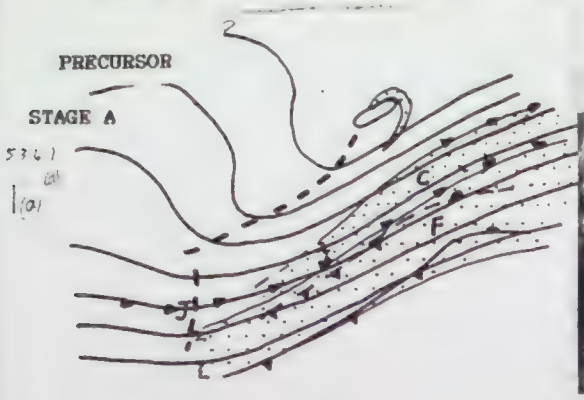
* Strong upward motion accompanies formation of hook B, the area with brightest cloud tops on 11UTC VIS image

* Negligible vertical motion accompanies cloud area C, which is therefore becoming less organised on the imagery

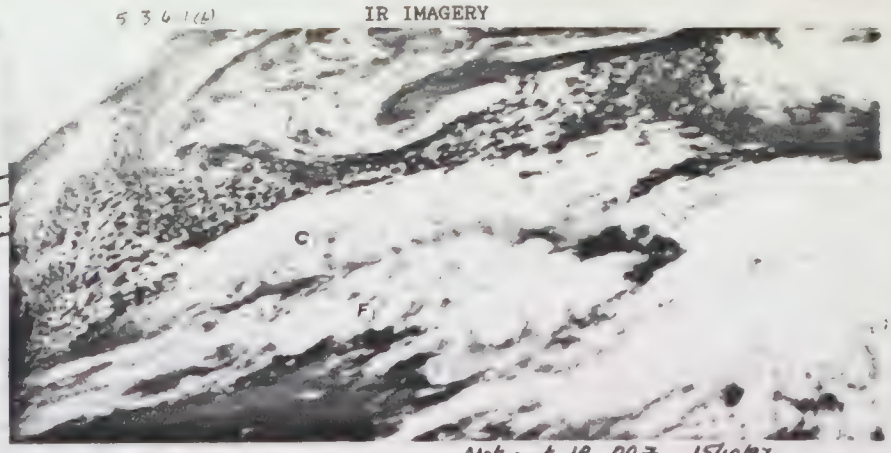
5.3.4A

TYPE 4A FLAT TROUGH, CONFLUENT FLOW

IDEALISED 300MB FLOW AND CLOUD OUTLINE



IR IMAGERY



Melbourne IR, 00Z 15/10/87

* Cloud areas C and F lie downstream of confluent upper trough axis

* C may have emerged from beneath F (as in Type 1), developed separately upstream (as in Type 3A), or formed from the cloudband of an old occlusion

* C is layered: coldest tops towards poleward side. Associated with a frontogenetic region

* F is broad band of upper cloud; its thickness varies from case to case - sometimes dense with lumpy tops, sometimes virtually absent

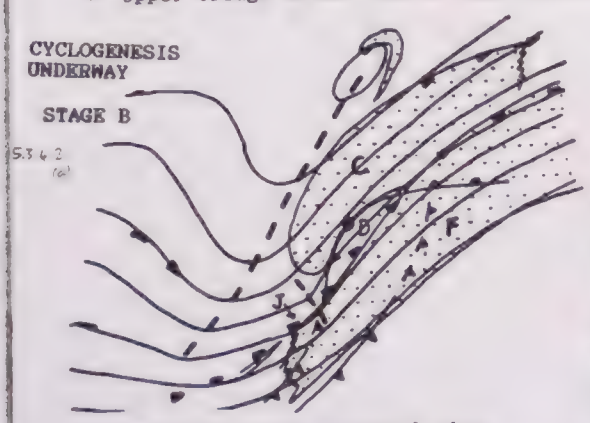
* Poleward edge of F denotes jet axis. May be separate jet poleward of C or broad region of strong upper winds

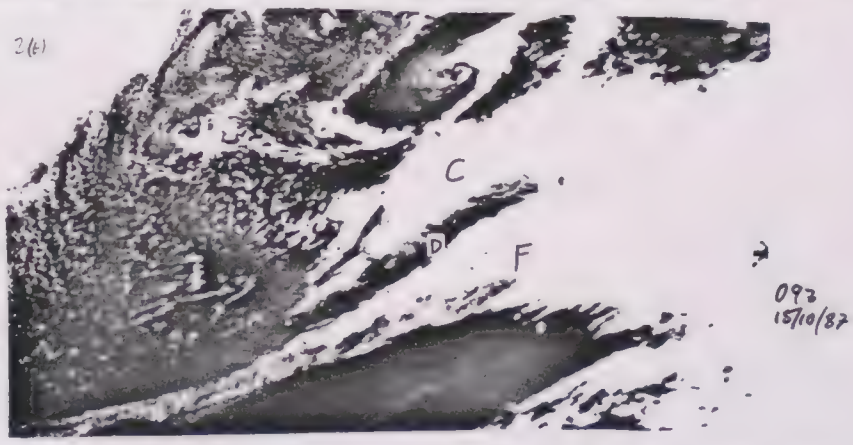
* Upper trough often flatter than shown in the schematic

* There may be no evidence at this stage of jet streak J or its associated short-wave

* J may have originated upstream of the upper trough e.g. pXXX OR

J may not appear until stage B in which case it seems to form ahead of the upper trough e.g. pXXX





* C develops convex poleward edge

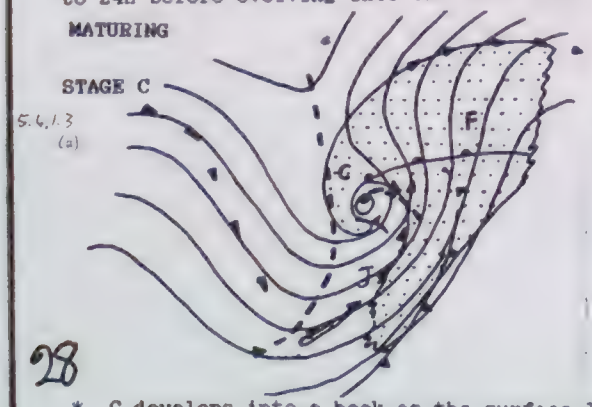
* Narrow cloud-free or "dry wedge" D appears between C and F

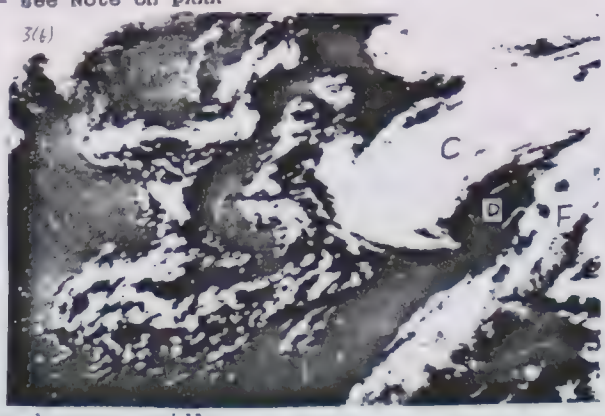
* F often dissipates upstream of C

* A new jet maximum J forms ahead of the major trough, by which time a new short-wave (dashed line) has often started to form just to rear of C - sometimes signalled by growth of cirrus along poleward boundary of F

* C and F may coexists in this form retaining the same shape for up to 24h before evolving into the next stage - see Note on pXXX

* The CLOUD HEAD is a special case of this stage in which C is particularly broad (around 300nm) and well-defined and the dry wedge very prominent





28

* C develops into a hook as the surface low deepens rapidly

* C does not always wrap round depression centre as a distinct spiral; strong subsidence at base of hook often causes it to break up into separate elements which rotate around the low centre

* The jet has split - surface low now located at left exit of J

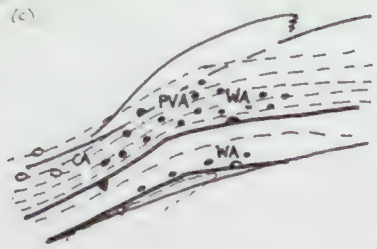
NOTE: NWP MODEL FORECASTS OFTEN FAIL TO DEEPEN THE SURFACE LOW SUFFICIENTLY, AND PLACE THE CENTRE TOO FAR FORWARD

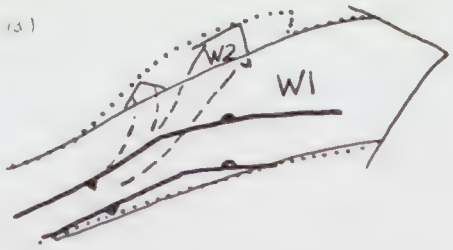
ADVECTION, VERTICAL MOTION AND THERMAL FIELDS

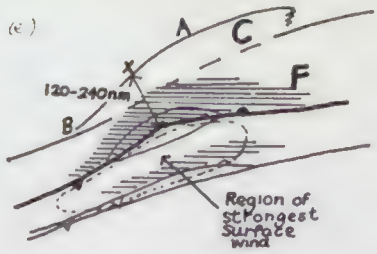
AIRFLOW MODEL

SURFACE ANALYSIS AND PRECIPITATION

534.1







* F formed by conveyor belt W1; usually contains sub-tropical air. C formed by conveyor belt W2 ascending polewards from beneath W1

* C and F correspond to separate frontal zones; poleward one often particularly strong. Shown by e.g. 850mb θ_w or 1000/500mb thickness

* C formed within region of strong ascent due to PVA. The ascending motion sometimes extends well forward of C due to WA - may cause minor waves on WF2

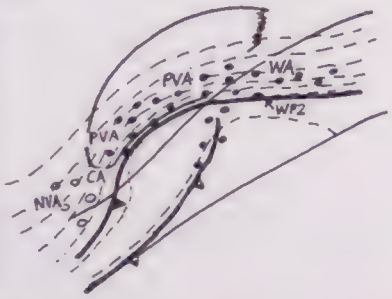
* Double frontal structure often present Equatorward front may only be an upper front

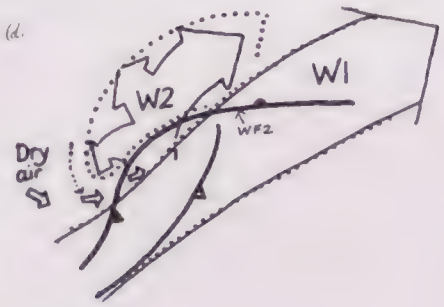
* Elongated depression containing severa non-persistent small centres beneath equatorward side of jet

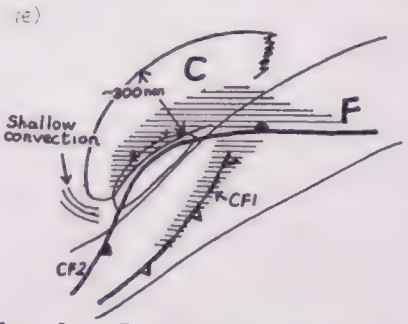
* Centre of gravity of depression lies adjacent to C midway between apex A and point B where C tucks beneath F

* **Strongest surface winds** found in warm sector

534.2







* C expands as W2 protrudes further from beneath F. C Consists of stratiform cloud produced by vigorous slantwise ascent of air over intensifying frontal zone WF2 *The air is unstable to slantwise ascent.*

* Core of very strong ascent now established along inner edge of C due to concentration of PVA ahead of short-wave

* Dry wedge consists of a "canyon" of dry air (originating in the region of subsidence caused by NVA/CA upstream) which has until now been obscured beneath the veil of cirrus associated with F.

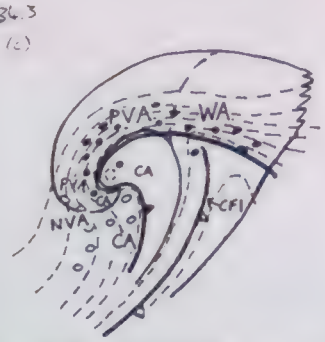
* **Surface low**: Rapidly deepening, elongated, situated beneath dry wedge, just poleward of jet. Centre most likely towards rear of C. Very sharp warm front

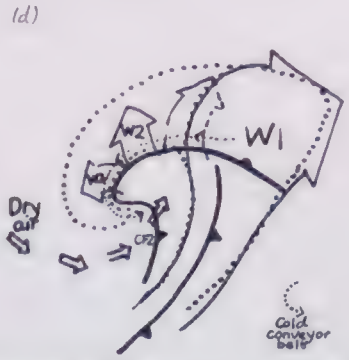
* **Strongest winds** still in warm air, but expect strengthening flow to rear of C; often indicated by streets of shallow convection

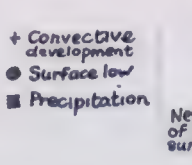
* CF1 often poorly defined by surface θ_w

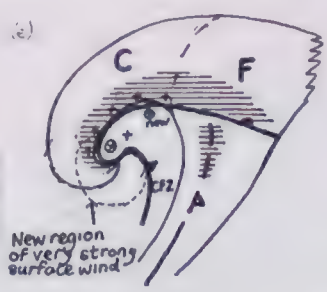
* **Precipitation**: very heavy along inner edge of C associated with ascending air in W2; embedded thunderstorms likely. Narrow band of heavy rain on CF1. New rain areas may develop between CF1 and CF2

536.3









* Strong ascending motion and intense thermal gradient extends around inner edge of C; secluded warm core forms over depression centre

* Weakening ascent along CF1

* CA/NVA occurs behind the marked short-wave located just to rear of surface low. Causes strong subsidence; rapid pressure rises result in tightening of pressure gradient and very strong winds to rear of low

* Shallow CCB (dotted arrow) moves around the west of the depression in the strong low level flow; seen as a trail of low cloud emanating from beneath C and is leading edge of cold air behind CF2

* Ascending motion within dry slot due to dominance of PVA

* **Surface low**: normally within base of hook. New centre may form further along edge of C towards F if C is very elongate

* **A new region of particularly strong surface winds** will be present at the base of the hook, located just behind CF2

* Precipitation: as above, but rain along CF1 normally weakens. Deep convection may develop beneath cloud-free slot

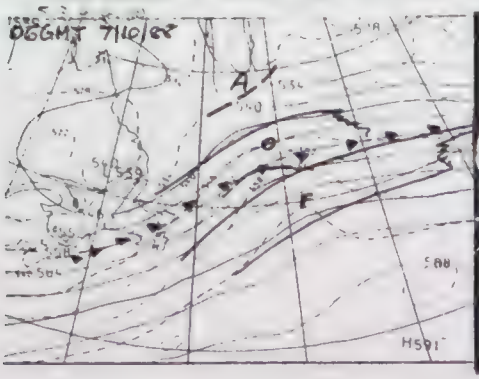
* Little precipitation on CF2; introduces much lower θ_w at surface

EXAMPLES OF THE EVOLUTION OF TYPE 4A CYCLOGENESIS :- 7-8/10/88

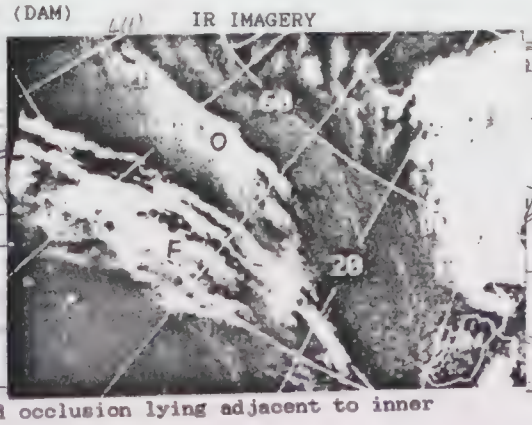
BROAD SCALE

The following example illustrates one way in which a cyclogenetic cloud signature may evolve in a Type 4A upper air pattern. The poleward portion of the main upper trough sometimes moves forward as a short-wave (labelled A in this example) which acts as a trigger for cyclogenesis as it engages the surface depression.

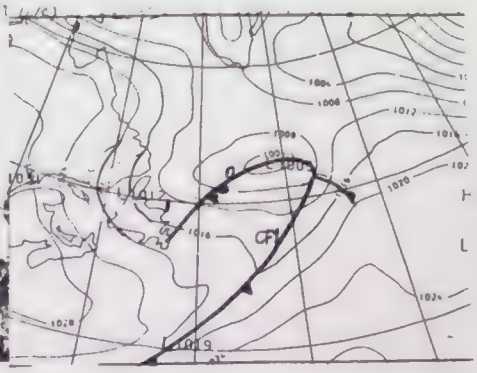
500MB HEIGHT + 1000/500MB THICKNESS (DAM)



IR IMAGERY



Surface analysis



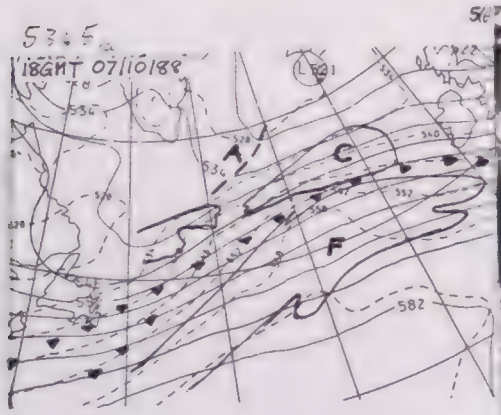
* Elongated cloudband O is an old occlusion lying adjacent to inner frontal band F

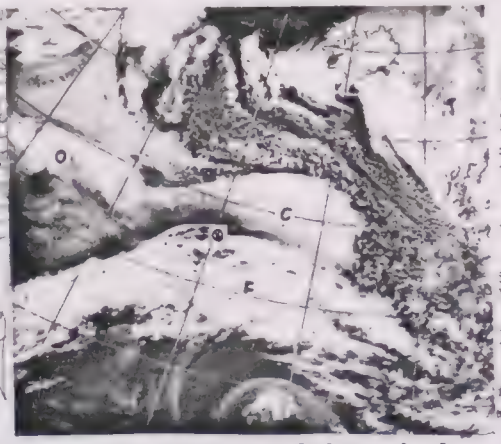
* The major thermal gradient corresponds to band O

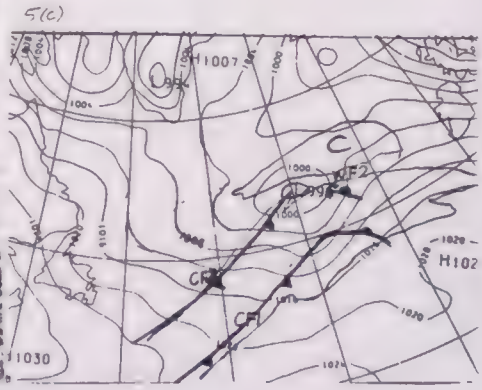
* The whole system lies in a region of strong zonal flow ahead of a confluent upper trough

* Jet axis located between O and F

* An elongated depression lies along inner edge of cloudband O







* A separate layered cloud leaf C becomes detached from O forward of short wave A. The cloudband O, extending westwards along 55N has fractured behind the short wave A

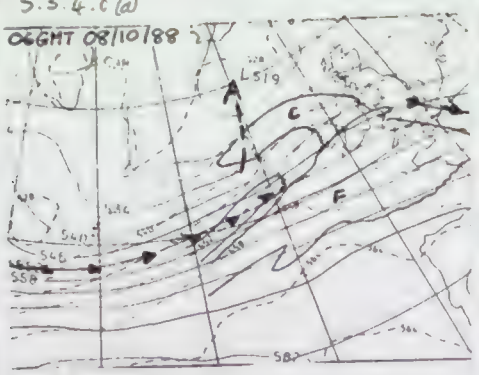
* C is a new region of slantwise ascent, inferred from progression from warm to cold cloud tops from SW to NE. (Corresponds to new ascending conveyor belt W2 on schematic, p[illegible].) Indication of incipient cyclogenesis

* Deep convection undercuts C; implies strengthening thermal gradient beneath C reinforcing possibility of rapid cyclogenesis

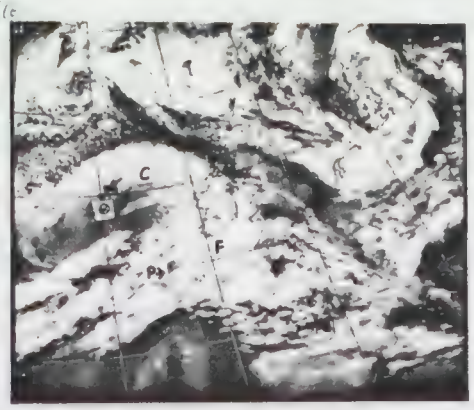
* The old occlusion O has been re-analysed as open wave comprising warm/cold front WF2/CF2 in view of the thermal pattern

* Deepening depression lies adjacent to rear portion of C and is about to become located beneath the dry wedge

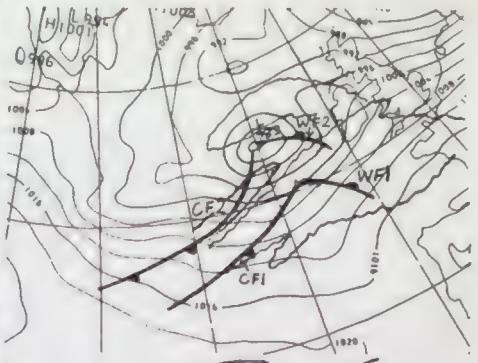
5.3.4.6(a)



6(c)



6(c)



* During rapid deepening of the surface low, the poleward edge of C develops more marked anticyclonic curvature

* A rather broad cloud-free wedge penetrates between C and F

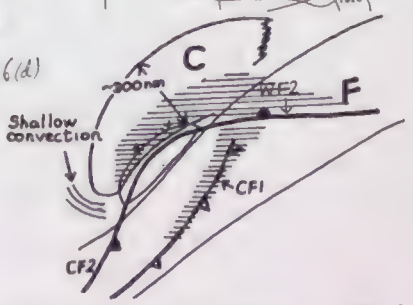
* Pockets of lumpy mid-level convection P near tip of minor wave on inner front; indicates heavy rain likely beneath F

Note phase error in NWP upper air fields - thermal wave associated with C is too far forward

Differences from schematic figure:

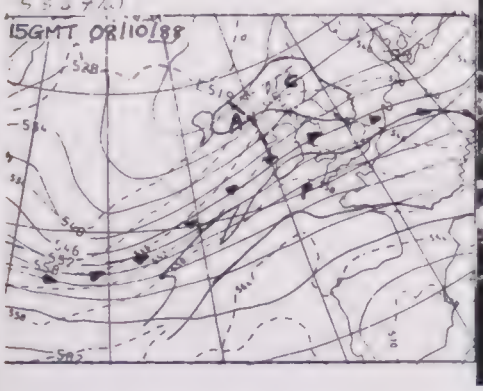
* The dry wedge is particularly broad, whilst the northern cloudmass C becomes less well-defined and more ragged with time. This often implies that the depression will not be of unusual intensity i.e. gales rather than hurricane-force winds

6(d)

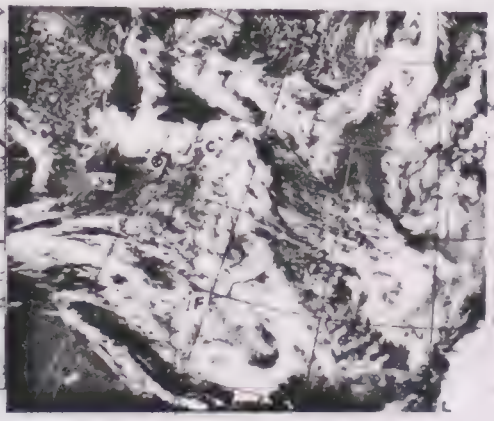


Difference from schematic: WF1 is still identified as a separate feature. (It normally becomes indistinguishable from the strong thermal gradient of WF2.)

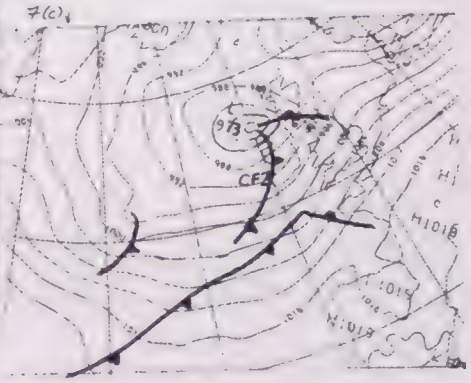
5.3.7(a)



7(c)



7(c)

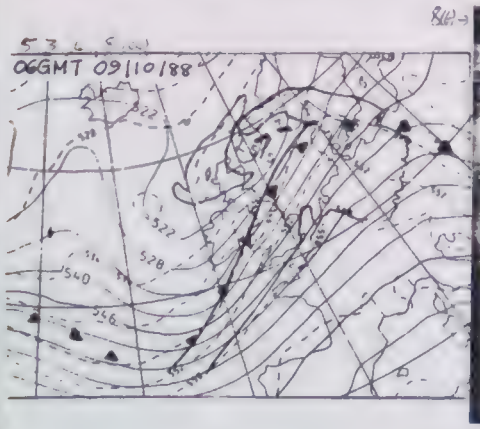


* The swirl of low cloud S indicates that a vigorous surface circulation now exists; S marks the low-level vorticity maximum which usually lies within 60nm of the lowest surface pressure

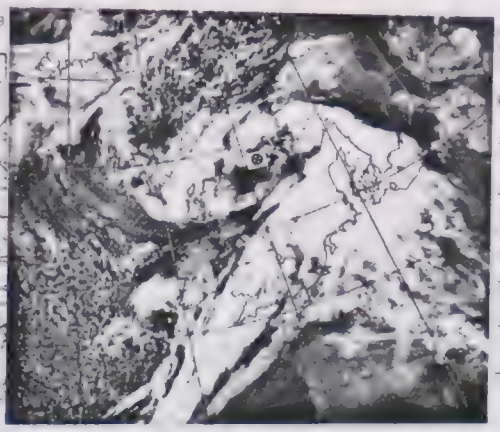
* Narrow streets of convection indicate strong surface flow in the cold airmass just to rear of the depression

* CF2 lies at rear edge of shallow layered cloud

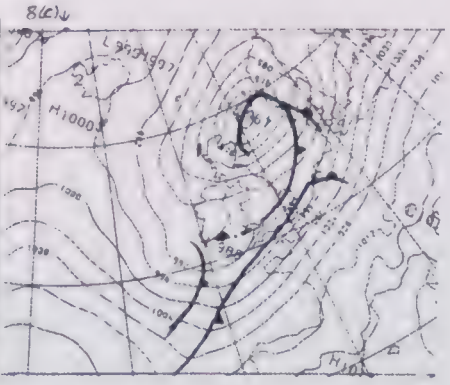
5.3.6(a)



8(c)



8(c)



* The depression has finished deepening now since the upper cloud has moved right around the depression implying a closed circulation aloft

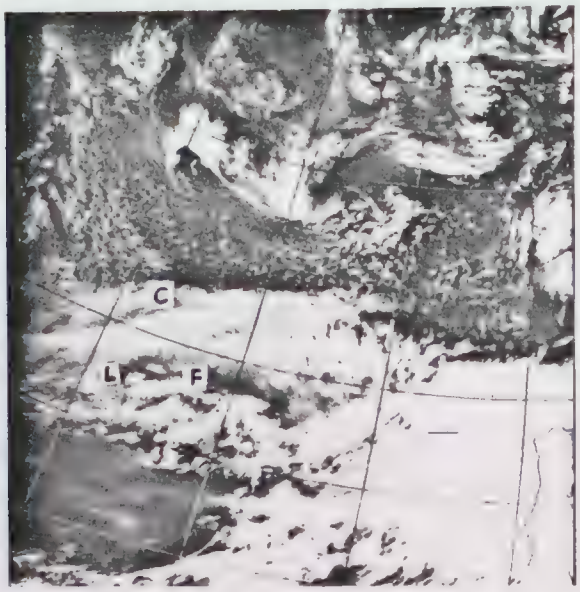
Note that separate rainbands are often associated with C and B, with a gap between.

TYPE 4A: EVOLUTION OF A CLOUD HEAD DURING EXPLOSIVE CYCLOGENESIS

This example illustrates the development and evolution of a cloud head which preceded explosive cyclogenesis. The depression centre crossed the UK observing network during its most intense phase causing hurricane-force winds at a few locations.

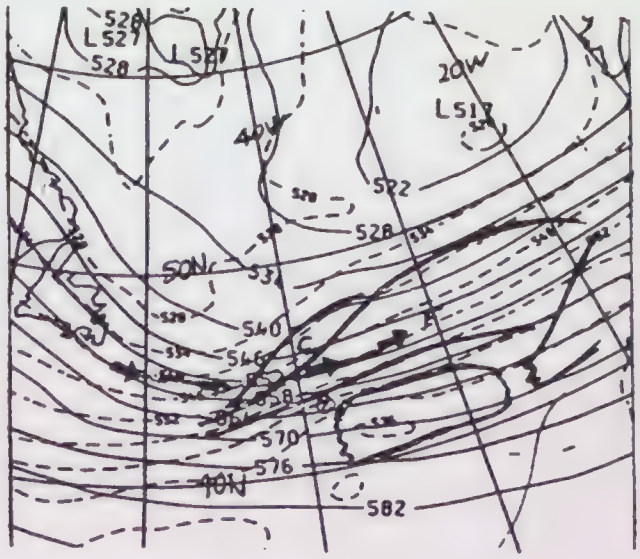
1. SATELLITE IMAGERY

5.4.3.9 (a)



1640z 14/10/87

5.4.3.9(b)



Precursor

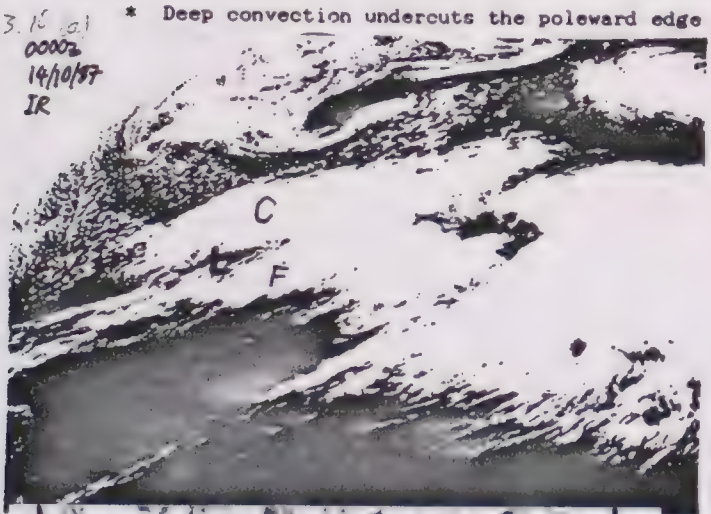
* Large mass of upper and middle cloud comprising cloud areas C and F, lies within a strong baroclinic zone on the forward side of a flat and marginally confluent upper trough

* Area of mid level cloud C is beginning to appear on the poleward side of the primary baroclinic zone cloudmass F

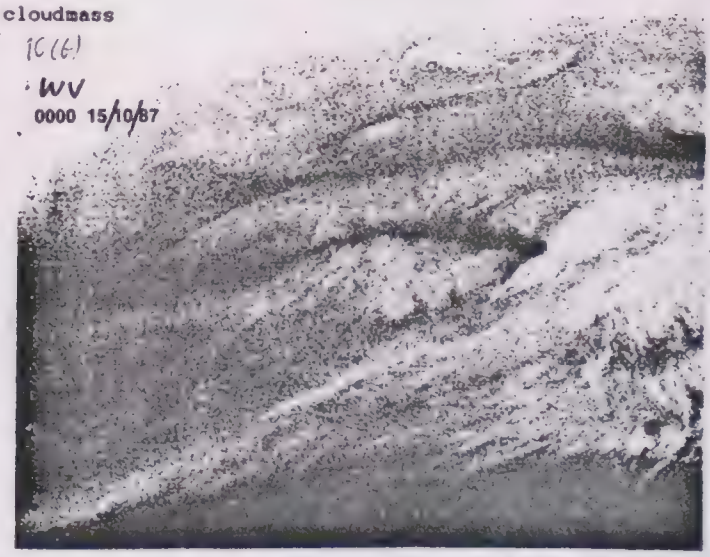
L = Surface low

* Deep convection undercuts the poleward edge of the cloudmass

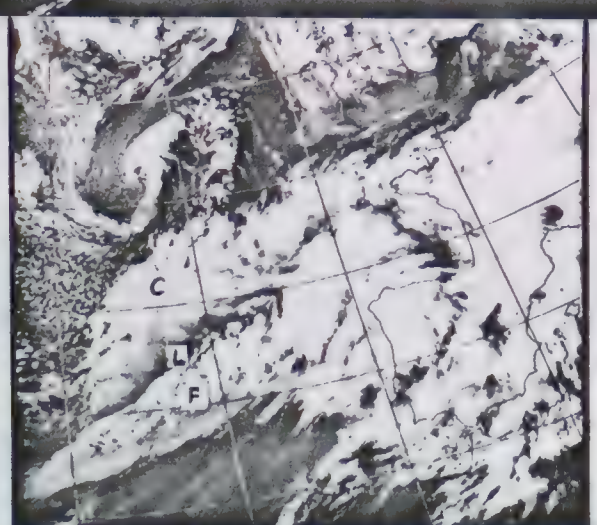
5.4.3.10 (a) 0000z 14/10/87 IR



10(b) WV 0000 15/10/87

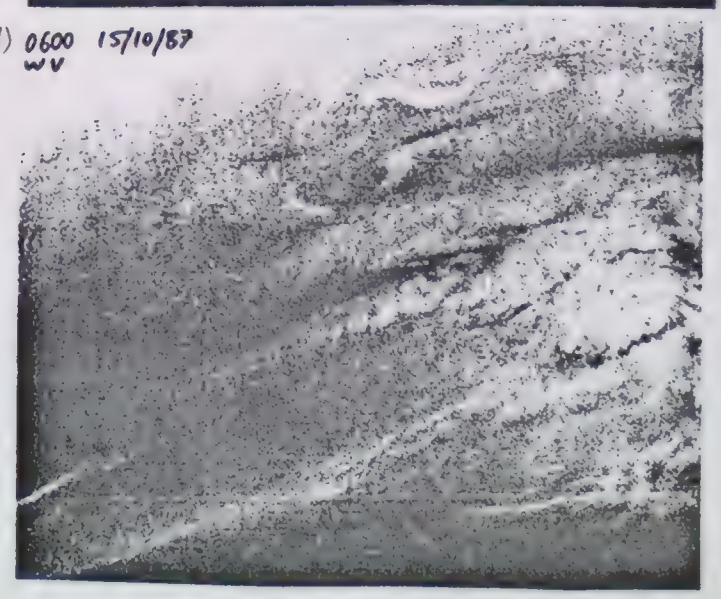


10(c)



0450z 15/10/87

10(d) 0600 15/10/87 WV

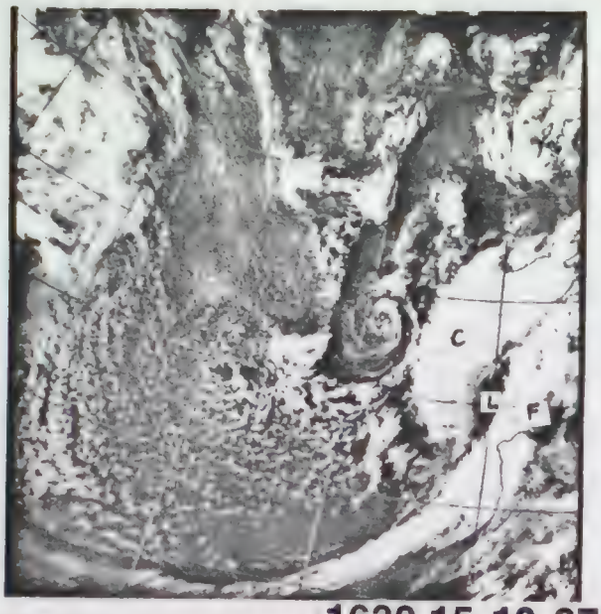


Cloud head formation (onset of rapid deepening)

* C is now a broad area of layered cloud lying immediately poleward of cloudband F and has a distinct anticyclonically curved poleward edge

* C exhibits a transition from warm tops on its inner edge and cold tops at its poleward edge.

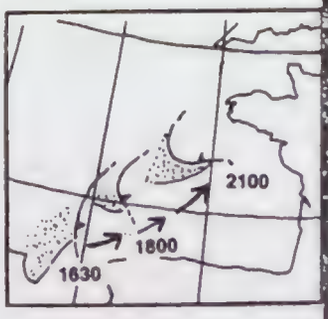
IR IMAGES

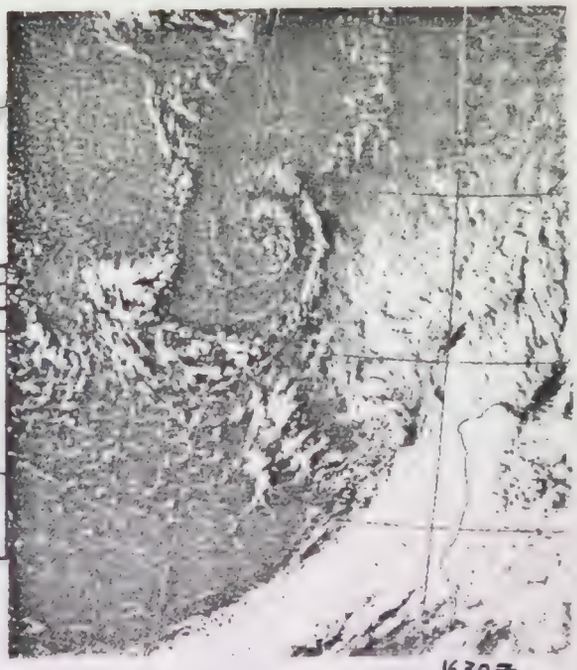


1630 15-10-87

VIS IMAGE

5.3.4, 11(a)





1630Z 15/10/87

Rapid deepening

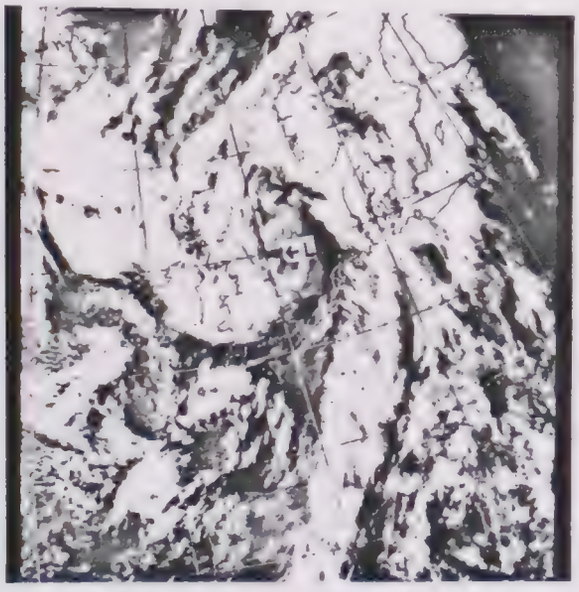
~~IR IMAGES~~

* Cloud head signature persists - an important clue that rapid deepening is occurring

* Surface low situated on inside edge of C beneath the dry wedge

* Rope-like cloud structure N situated on the inner edge of C marks location of surface cold front

* Inset shows position of front N and leading edge of cloud (stippled) within rear part of head at 1630UTC and subsequent times. More detail on the analysis on pXXX 37



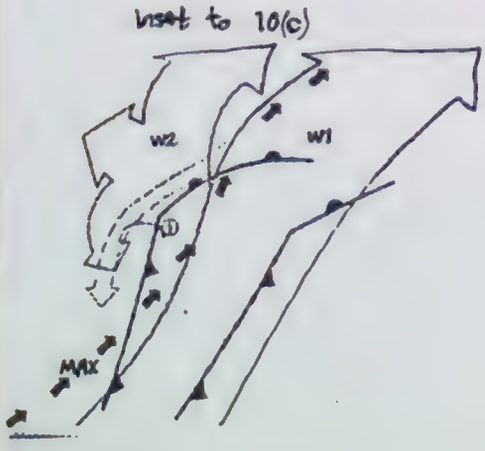
5.3.4, 12

0820Z 16/10/87

Mature stage

* The tip of C has just begun to wrap around the depression centre implying that deepening of the depression is complete

Inset to 10(c)



2. RELATIONSHIP BETWEEN DYNAMICAL PROCESSES AND FEATURES ON THE IMAGERY

On the facing page diagnostics are presented from a NWP model forecast to explain the relationship between the main dynamical forcing mechanisms and the features on the imagery as represented by the model's 400mb humidity field. The main features of interest are:

(i) **Cloud head C and dry wedge D**

(ii) **Jet streak J and associated shortwave trough A** which engage the surface low

(iii) Upper level **potential vorticity maximum V** which represents a downward extrusion of stratospheric air which engages the surface low culminating in rapid deepening (see overleaf p~~XXX~~ 36)

T+0 (Fig. 5.3.4.13)

* Flat trough with strong flow around the base

* Jet streak J originates from upstream; some evidence of short wave A in the contour pattern

* The two areas of upward motion (hatched) correspond to small lows within the elongated trough; forward one largely warm advection dominated

CLOUD HEAD FORMATION T+6 (Fig. 5.3.4.14)

* **C expands as upward motion (maximum value exceeds 90mb/h) becomes concentrated over rearward low, ahead of intensifying short wave A**

* **Injection of upper level dry air D equatorward of C signifies formation of dry wedge seen on imagery as jet J moves forward**

* Depression is now located in left exit of J

T+12 (Fig. 5.3.4.15)

* Short wave A and jet J progress around upper trough

* Poleward edge of C becomes anticyclonically curved as the upper flow distorts

* Surface low in marked left exit - right entrance couplet; persistent of core of strong upward motion on inside of C

* **Marked subsidence (open circles) begins at rear of C immediately behind A**

T+24 (Fig. 5.3.4.16)

* Short wave A now overlies surface low - deepening virtually complete

* Expanding area of subsidence behind A; large contribution due to cold advection in this region

KEY (left hand column)

~300mb height (dam)

Selected 300mb isotachs (kn)

@ Surface low centre

700mb ascending motion > 30mbh^{-1} (9.3 cm/s)

400mb RH > 90% (Shown only in vicinity of cloud head)

KEY (right hand column)

~PMSL (mb)

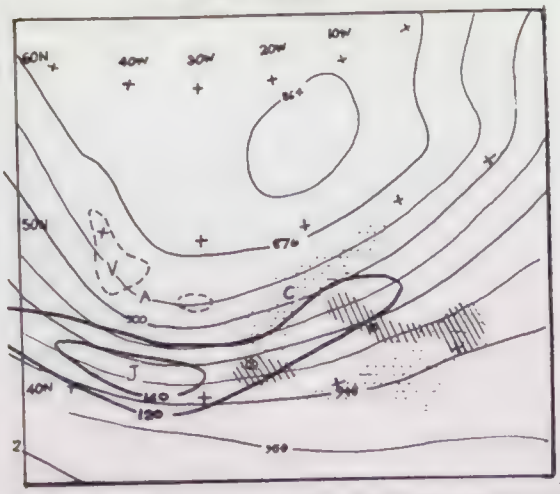
400mb RH = 40% (Shown only in vicinity of cloud head)

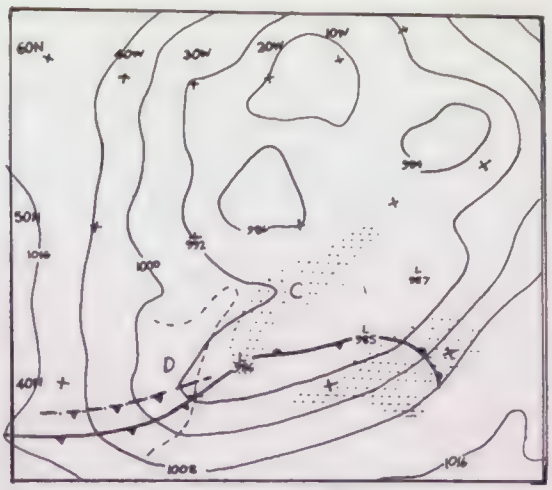
700mb descent > 10mbh^{-1} (3 cm/s)

DYNAMICAL FORCING FEATURES

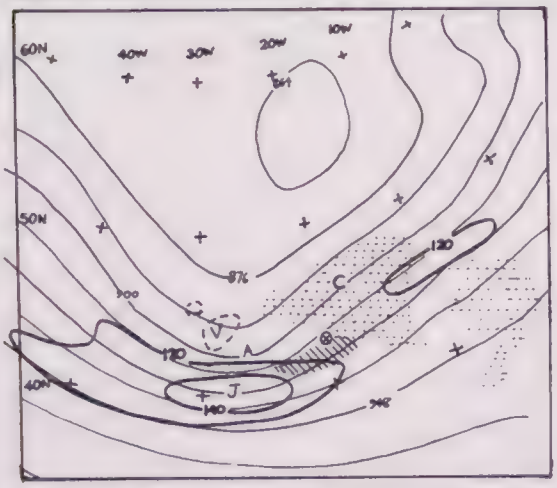
SURFACE FEATURES AND UPPER LEVEL MOISTURE

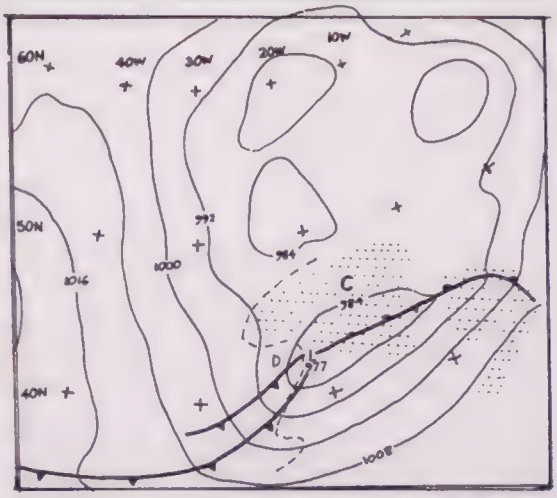
T+0



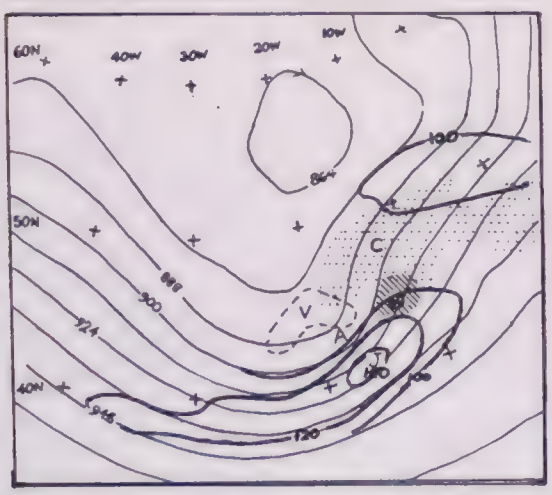


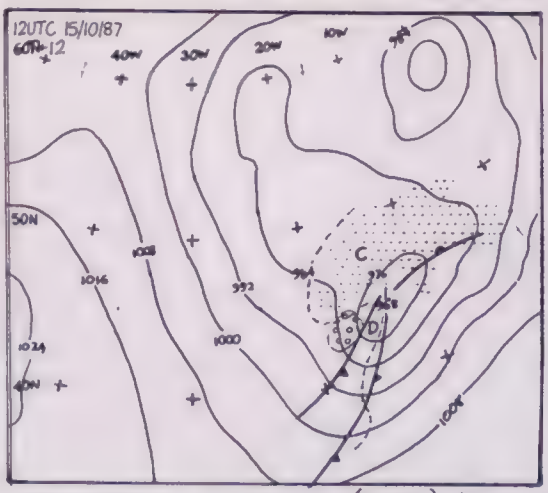
T+6



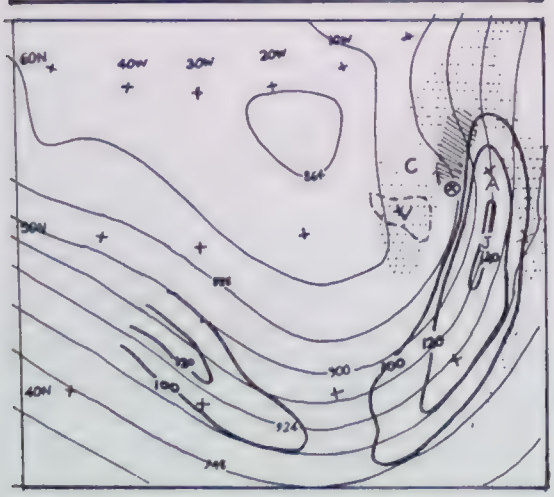


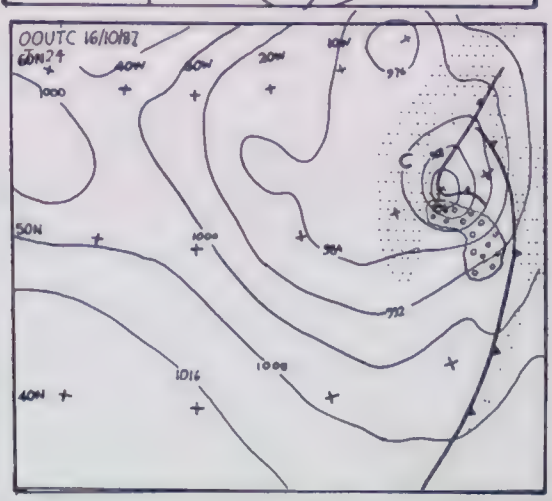
T+12





T+24



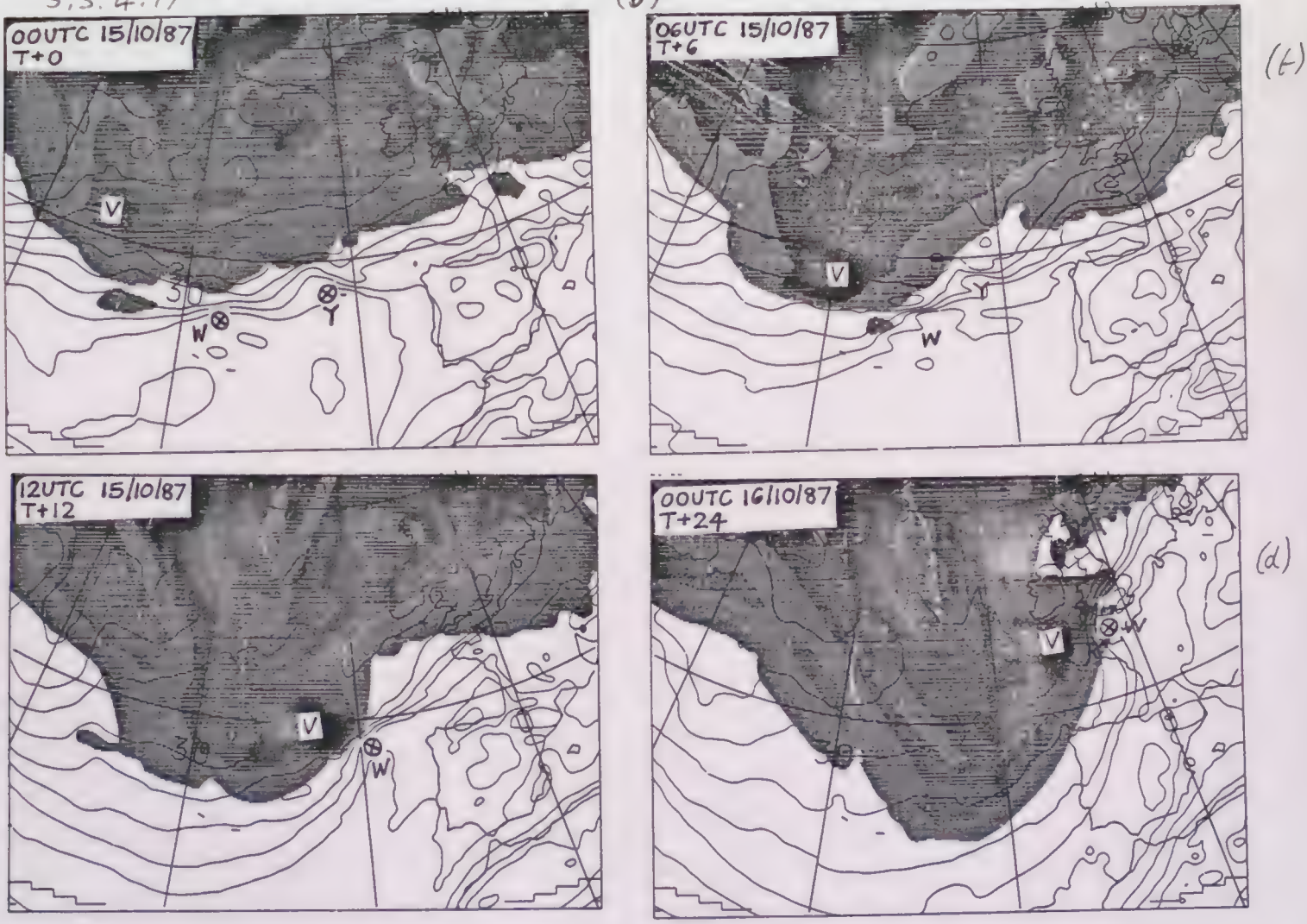


Potential vorticity perspective

An alternative means of explaining cyclogenesis is in terms of the behaviour of the potential vorticity (PV) field - in this case on the 330K surface. In particular, the onset of rapid deepening is attributed to PV anomaly V phasing in with low level warm anomaly W represented by the 900mb temperature field.

PV is a potentially useful means for identifying upper level trigger on NWP output as values are conserved on an isentropic surface for motion of dry air parcels (Ref. Hoskins et al. 1985)

5,3.4.17



T+0: Initially two warm anomalies exist, labelled W and Y; each is colocated with shallow surface low (circled cross)

T+6: V rapidly moves into phase with W promoting onset of rapid deepening of its associat ed surface low. Meanwhile, Y loses its identity

This "phasing-in" appears to coincide with cloud head formation. V forms part of the dry wedge that is so prominent on WV imagery

T+12: Whilst the low level warm anomaly W and associated surface low are both phase-locked immediately ahead of V, continuing intensification of the surface low occurs

T+24: The forward part of V becomes detached above the surface low which has now, as a result, reached its maximum intensity

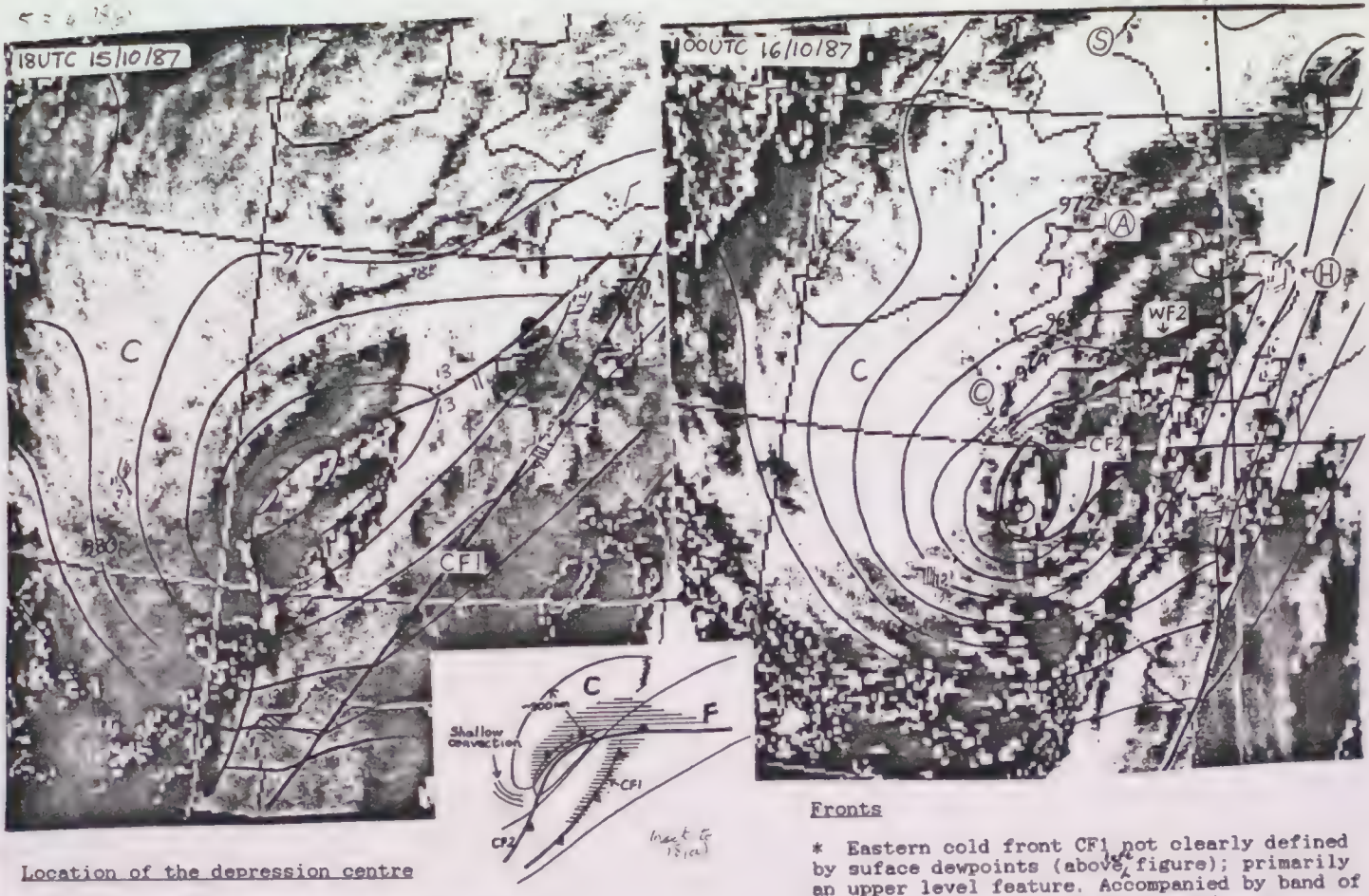
KEY

White PV < 2 units
Pale gray 2-6
Dark gray 6-10
Black >10

~ 900mb isotherms 2.5K intervals

⊗ Surface low

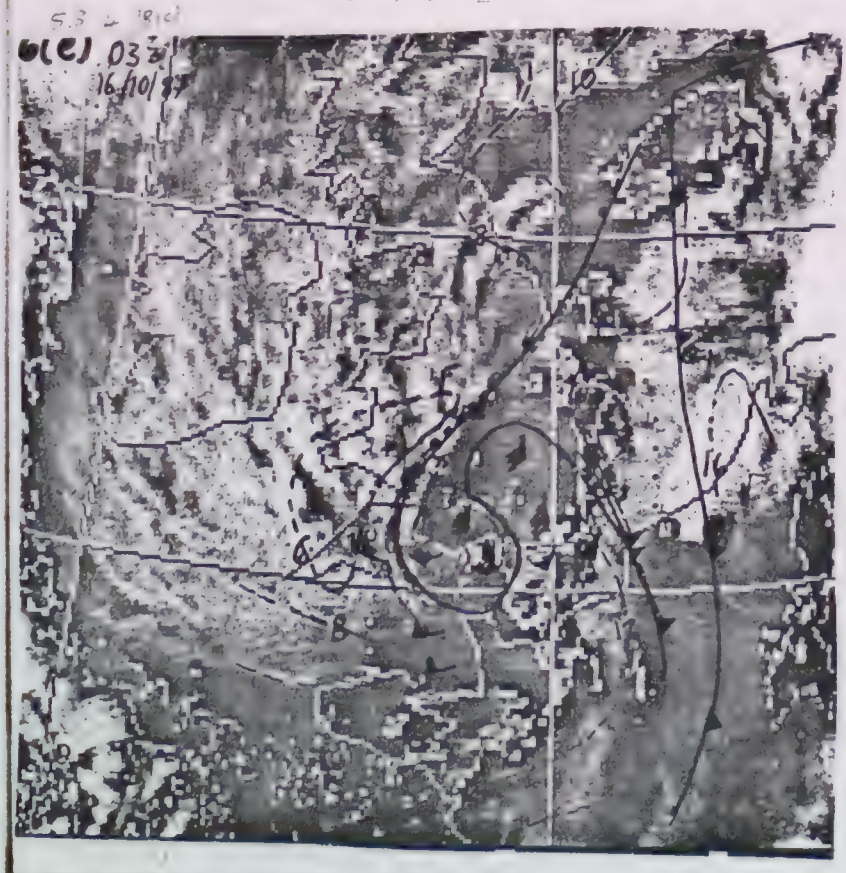
Note: Despite the assertion that PV should be a conservative quantity, the maximum value of V increased during the first 3 hours of the forecast sequence for some (as yet unidentified) reason. The location of V at T+0 is therefore based on continuity.



Location of the depression centre

* Beneath the dry wedge along inner edge of hook C

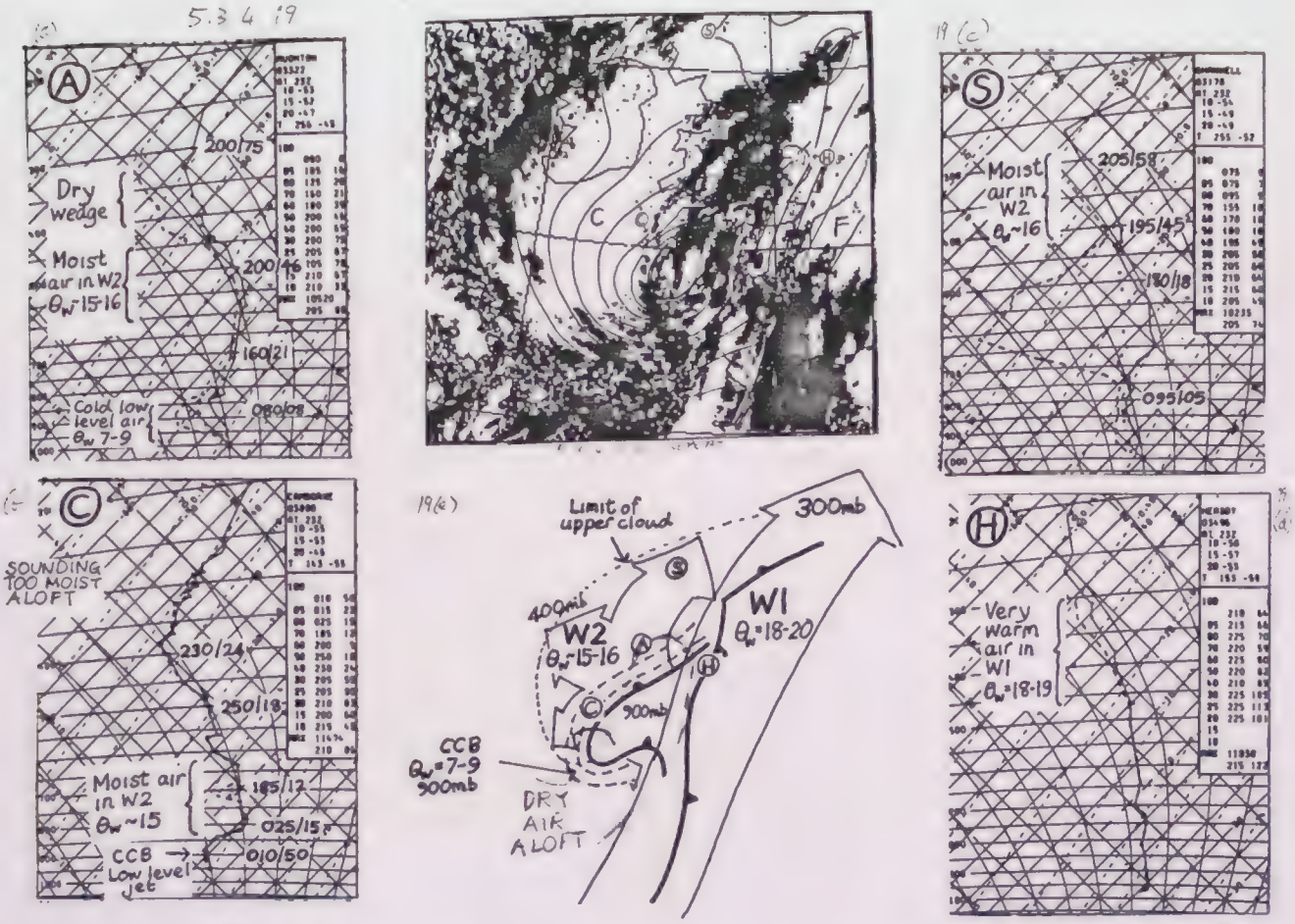
* Lies within a region of very strong horizontal thermal gradient



Characteristic radiosonde soundings during cyclogenesis

This case demonstrates the likely appearance of radiosonde ascents made through the various imagery components of the depression. The soundings are explained in terms of conveyor belts. Such information can provide a useful basis for human intervention in model analyses where actual data is sparse.

(A) (C) and (S) are soundings made through the poleward cloud shield, whilst (H) is though the equatorward cloud shield. For characteristic sounding in dry wedge see p~~XXX~~ (03/02/90).



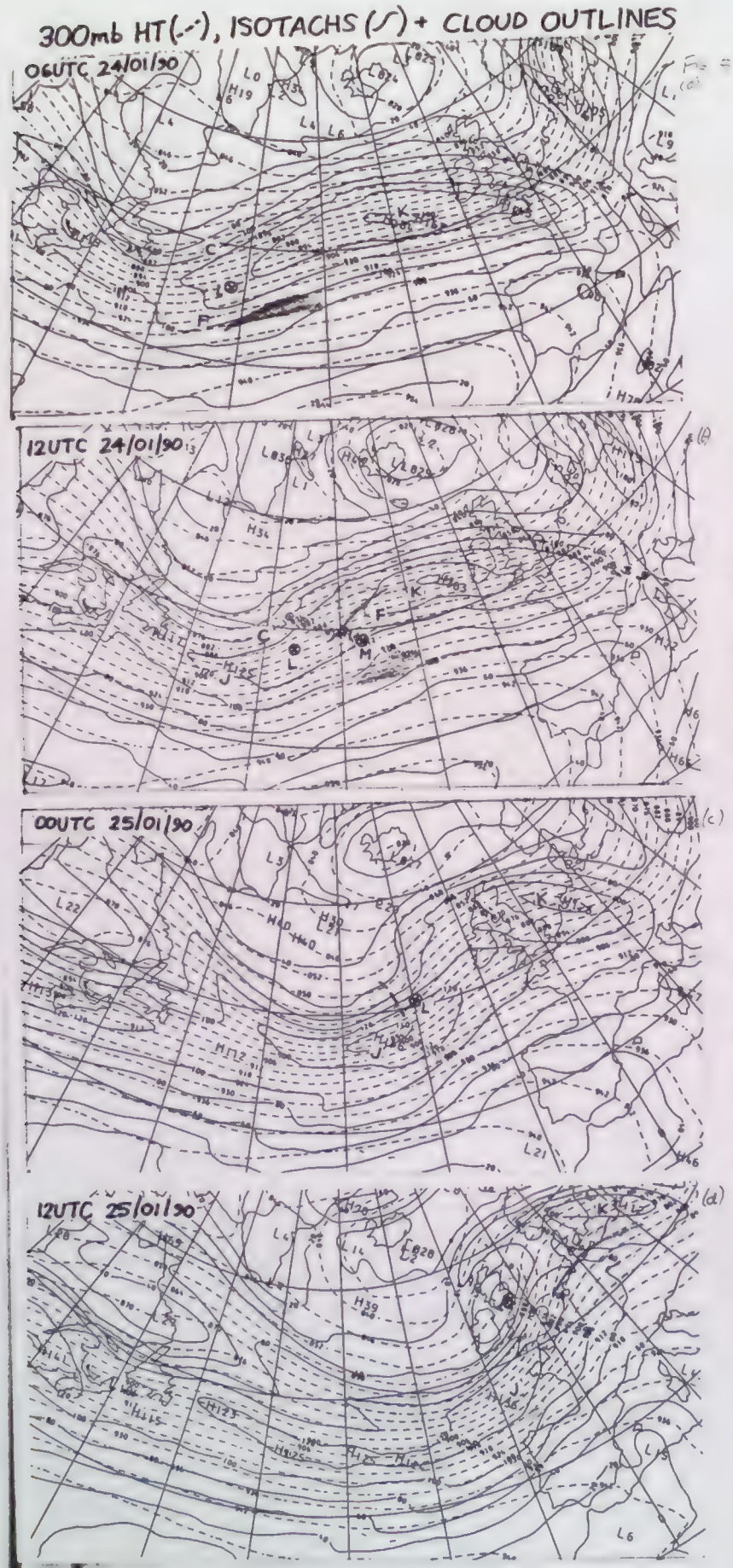
The main conveyor belts and their relation to the soundings are shown in the Table below:

TABLE 1

	CHARACTERISTICS OF THE CONVEYOR BELT	REPRESENTATIVE SOUNDING
W1	W1: Consists of gently ascending subtropical air of θ_w=18-20C. Found aloft, above about 600mb; contains embedded mid level instability	Deep layer of moist air at Hemsby (H) located on inner front. Uncertain precisely at what level the base of W1 lies, but the very high θ_w air is elevated in the upper troposphere
W2	W2: Originates in the warm boundary layer near the depression centre; characterised by θ_w =15-16C. Ascends rapidly over intense warm front	The sonde intercepts W2 where the sudden transition to moist air of θ_w=15-16 takes place combined with a marked increase in southerly wind component: i.e. around 850mb at Camborne (C), 600mb at Aughton (A) and 400mb at Shanwell (S).
CCB	CCB: Cold conveyor belt; Shallow layer of moist, rain-cooled air of θ_w =7-9C originating north of the warm front. Emerges from beneath W2	Very shallow layer of cold air around 900mb e.g. Camborne, accompanied by marked low level N'ly jet.
DRY FLOW	Dry flow: A deep layer of recently subsided mid and upper level dry air that originates upstream, separates W1 and W2. It overruns part of W2 and undercuts W1	The forward portion of the dry wedge can be seen overrunning W2 at Aughton (A) above 450mb, leading to a shallow layer of potential instability and a favourable environment for mid-level convection

TYPE 4A EVOLUTION OF THE JET DURING CYCLOGENESIS

Fig. ~~xxx~~ 13-16, p~~xxx~~ 34-35 (15/10/87) showed a clear example of cyclogenesis occurring as a jet streak moved from upstream of a flat trough to impinge upon a minor frontal wave. A somewhat more common alternative scenario is shown in the following figures - a new jet streak develops and strengthens on the forward side of a confluent trough immediately following cloud head formation.



* The cloud head has formed within the previous 6 hours as F moved rapidly east revealing the large dry wedge

* As in 15/10/87 case, two surface lows are initially present within an elongated pressure trough, the rearward one L associated with cloud area C. L subsequently deepened explosively

* L and M originally situated in right entrance region of elongated jet stream, with K as the downstream wind maximum. Soon after the cloud head formed, new jet streak J appears near the base of the trough

* J situated in clear air; occasionally delineated by rapidly moving cirrus fibres

* J has strengthened; rapidly deepening low centre now collocated with the left exit of J

* Minor upper level short wave (bold dashed line) just discernable at rear of C, immediately upstream of surface low

* The intensifying upper shortwave is now situated directly over surface low therefore deepening virtually complete

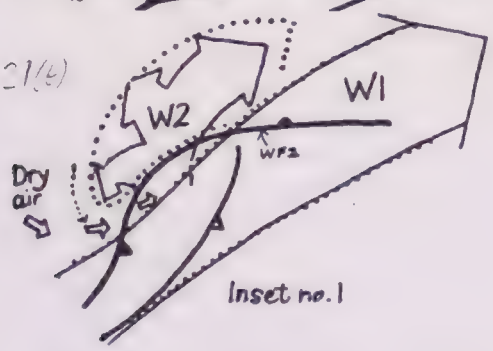
FURTHER EXAMPLE OF A CLOUD HEAD 18UTC 30/01/88 STAGE B

This example shows a cloud head situated south of Greenland. The associated rapidly deepening surface low is well-defined by an unusually large number of ship reports and demonstrates many aspects of how the analysis relates to the imagery.

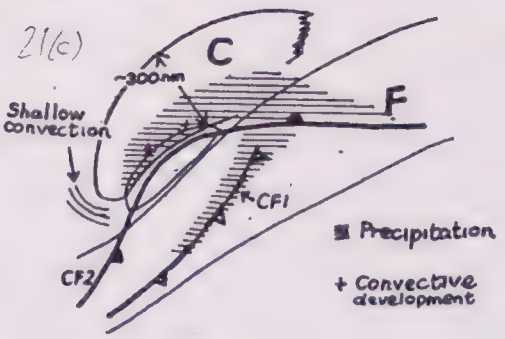
1. Imagery and analysis

5.3.4.21 (a)

21(b)



21(c)



* The two portions of the overall cloud canopy, F and C, are formed by ascending conveyor belts W1 and W2 which correspond to the two separate frontal systems comprising CF1 and CF2/WF2 - see inset no. 1

* C is a new region of vigorous slantwise ascent fed by W2 - see cross section

* Heavy rainfall occurs from W2 as it ascends over intense warm front WF2

* Surface low: Elongated; situated beneath dry wedge between cloud areas C and F - see inset no. 2

* CF1: indistinct from surface reports of temperature and dewpoint; it does however possess a strong thermal gradient above 800mb - see cross section

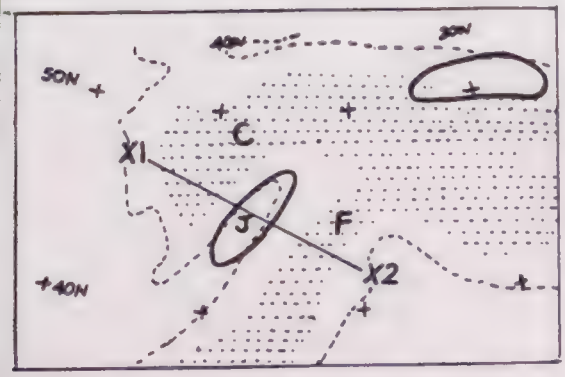
* Further development: in this case the central pressure fell by 25mb in the following 12h giving mean winds exceeding 65kn to the west of the British Isles

2. Cross-section through cloud head at the same time as the image (Fig. 5.3.4.21a, 5.0.18(d)-(f))

The introduction to Ch5 (p~~XXX~~ 11 Fig. ~~XX~~) explains how the formation of a cloud head can be visualised as a combination of a direct frontal circulation associated with the poleward frontal zone which is later reinforced by the indirect circulation associated with the upstream jet streak.

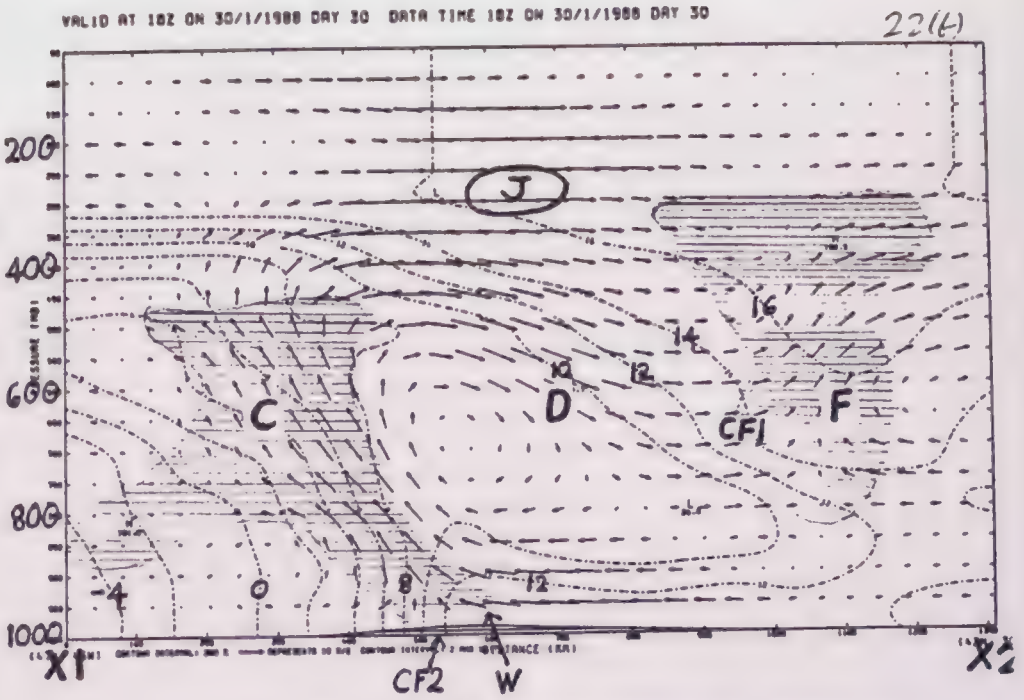
The NWP model-derived cross-section through this system clearly demonstrates how the dominant indirect circulation (i.e. arrows directed in a clockwise sense) associated with the new jet streak J gives rise to the vigorous slantwise ascent that results in cloud area C with its characteristic progression from warm tops to cold tops

5.3 4.22(a)



NWP model analysis of relative humidity; shading represents greater than 90% and pecked line, 40%. Bold outlines are 160kn isotach. X1-X2 is the line of the cross-section.

22(b)



Shaded areas are where relative humidity exceeds 90%. Arrows are components of ageostrophic motion tangential to the plane of the cross section combined with vertical motion. Dot-dashed lines are contours of θ_w. X1 and X2 are the western and eastern limits of the cross-section, shown as a dashed line on the image. J is the jet axis directed into the page.

The following features are highlighted by the cross-section, the location of which is shown on the image (as a dashed line) and the model 500mb humidity analysis for the same time

* Distinct cloud areas C and F

* The deep "canyon" of dry air D, separating C and F. D corresponds to the cloud-free wedge on the imagery. Relative humidity is less than 40% over much of this region

* Vigorous slantwise ascent within cloud area C

* The rearward-sloping zone of strong thermal gradient associated with C which is particularly marked at low levels. CF2 is the surface manifestation of this zone

* A well-marked frontal zone above 800mb associated with cloud area F and upper cold front CF1. The elevated high θ_w air is associated with conveyor belt W1.

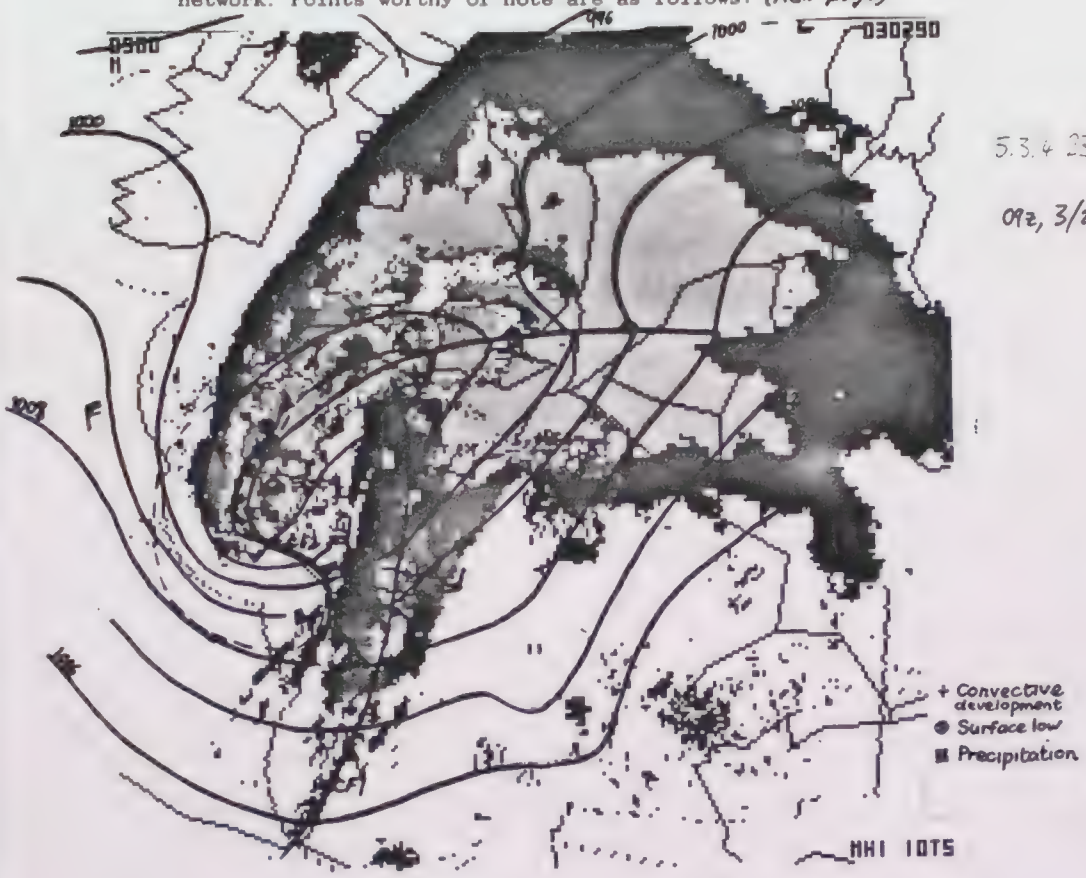
* Warm boundary layer air W which is the source region for the potentially unstable air which enters W2.

Note: The cross-section has the overall appearance of a split-front (Cross ref. Ch 4)

EXAMPLE OF TYPE 4A STAGE 3

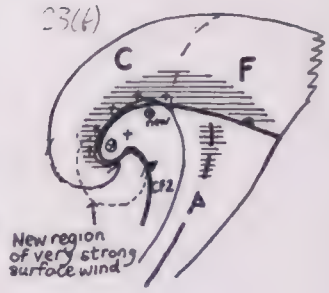
SURFACE ANALYSIS AND WEATHER DISTRIBUTION 03/02/90

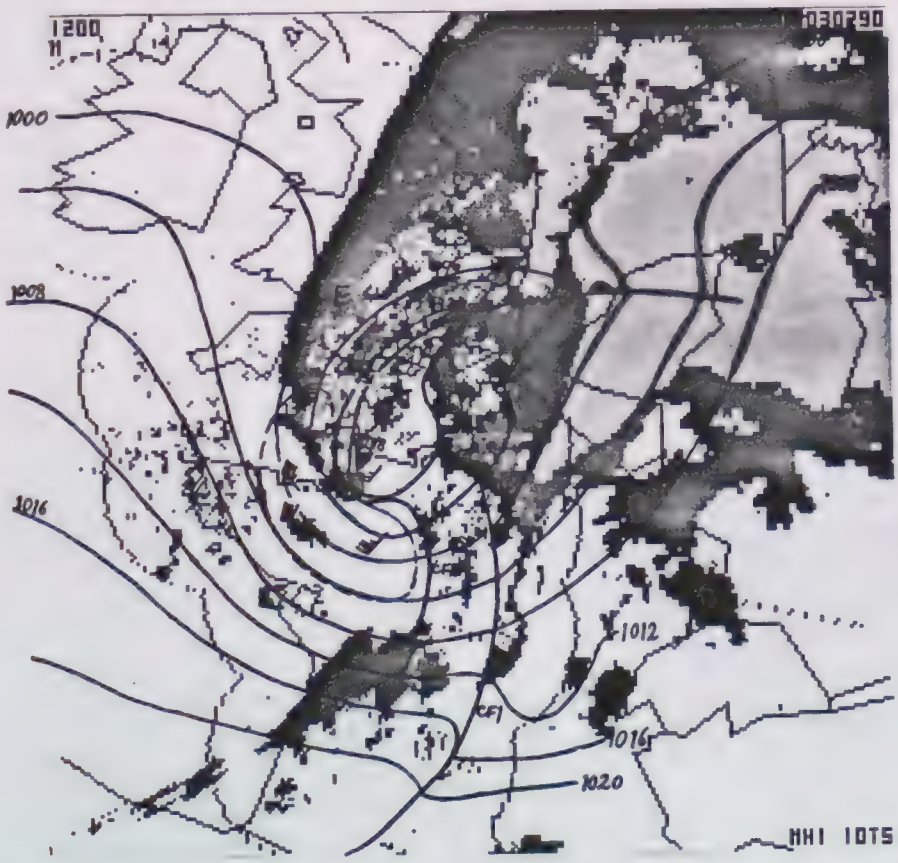
This particularly striking sequence of COST73 combined satellite and radar images shows the relationships between the cloud patterns on satellite imagery and the surface weather and analysis, described for the final stage of evolution in the schematic figure on pXXX (repeated below). Being a particularly small depression, the precipitation pattern has been almost entirely captured by the European radar network. Points worthy of note are as follows: *(next page)*



5.3.4 23(a)

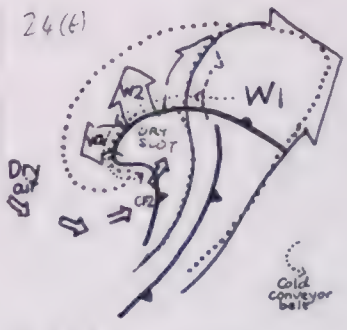
09z, 3/2/90

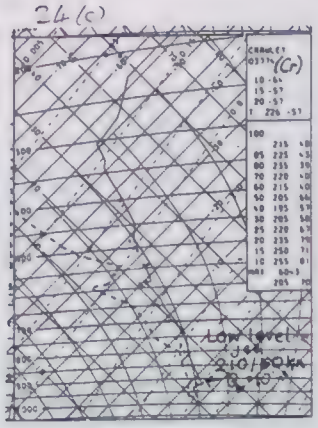




5.3.4. 24 (a)

12z, 3/2/90





Rainfall distribution

* A well-marked band of heavy precipitation extends around the inside of the hook C, and ahead of the very sharp warm front

* The narrow band of initially heavy rain along cold front CF1 on the 09GMT image progressively breaks up as it moves east

* Thunderstorms develop along the inner edge of C just on the cold side of the bent-back warm front

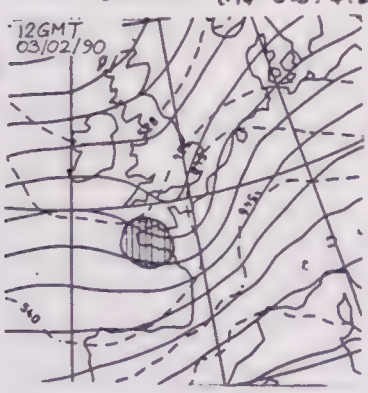
The precipitation distribution can be explained in terms of conveyor belts. Potentially unstable air lies within the dry slot as demonstrated by the 12GMT radiosonde sounding for Crawley (Cr). Air in W2 originates in the boundary layer of the dry slot i.e. at around 900mb in the low level jet, (characterised by θ_w =10C) and ascends strongly over the intense frontal zone. Instability is thereby released giving deep convection, up to around 500mb resulting in thunderstorms.

Suface analysis

* An elongated depression centre lies beneath the dry slot, parallel to the inside edge of the hook

* A core of very strong surface winds (some gusts over 80kn) has developed around the base of the hook (within the dashed outline). The onset of the strongest winds occurs with the passage of CF2.

* The strong pressure gradient to the rear of C becomes established due to very large pressure rises (up to 20mb/3h) which take place beneath the confluent part of the upper air pattern immediately behind the depression (Fig 5.3.4.24d)



Pressure rises >10mb/3h

EXAMPLE OF TYPE 4A 27-29 JULY 1988

This case demonstrates the following additional points

* A double cloud structure C and F on the image below, separated by dry wedge D, has important implications for predicting the rainfall distribution

* Techniques for locating the depression centre; i.e. beneath warm cloud tops adjacent to rear edge of C. Also marked later on by rapidly growing convection cells

* Sensitivity of NWP model performance to the representation of the upper air pattern in the vicinity of the depression

5.3.25

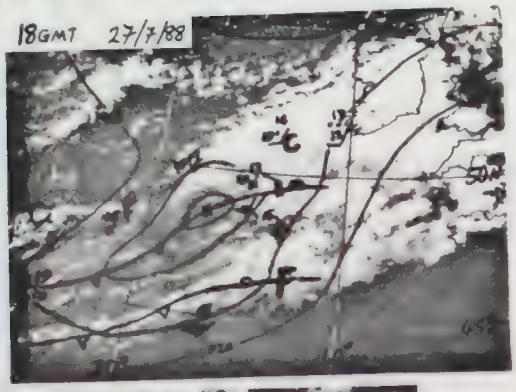


Fig. 5.3.4.25:

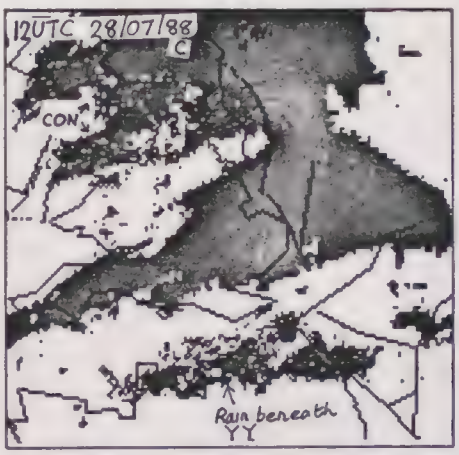
* C and F lie within strong upper flow forward of a confluent upper trough (not shown).

* F- narrow band containing lumpy cloud and therefore likelihood of middle level instability

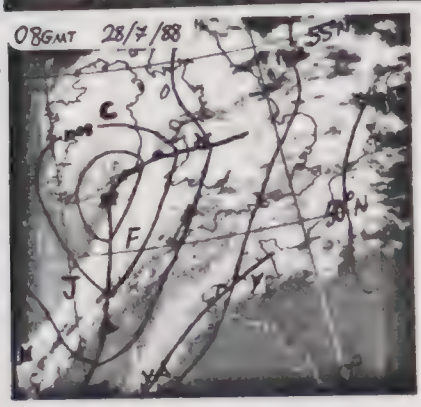
C and F had coexisted side by side for almost 24h with little development of surface low

* Filament of cirrus (CU) upstream may be first indication of new jet streak (see Ch 3); possible trigger for more rapid deepening

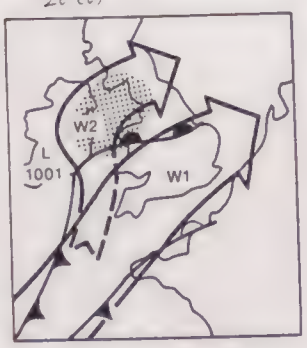
5.3.4.27



5.3.4.26 (a)



26(b)



* As low begins to deepen, the poleward edge of C becomes very convex (Fig. 5.3.4.26)

* Broad envelope of cloud F associated with older equatorward frontal zone extends from SW to NE across image. Caused by a gently ascending warm conveyor belt aloft, W1

* F comprises cloudband YY at its equatorward edge and XX along its poleward edge - XX delineates the jet axis

* Growth of cirrus XX may well be due to development of new jet streak J, located just upwind of C.

* In this satellite radar composite (3h after the adjacent satellite image) two distinct rain areas are present; one beneath C and one beneath F (Fig. 5.3.4.27)

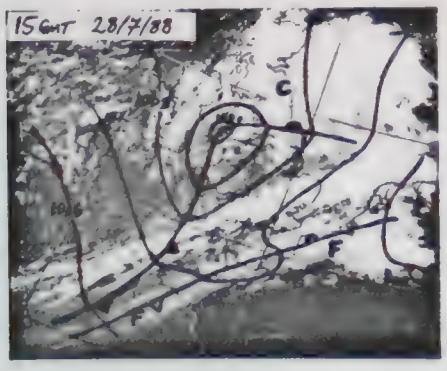
* C originates from secondary warm conveyor belt W2 ascending over the warm frontal zone

* Ascent combined with potential instability release within W2 produces bands of heavy convective rain beneath C, marked "CON" on satellite / radar composite image

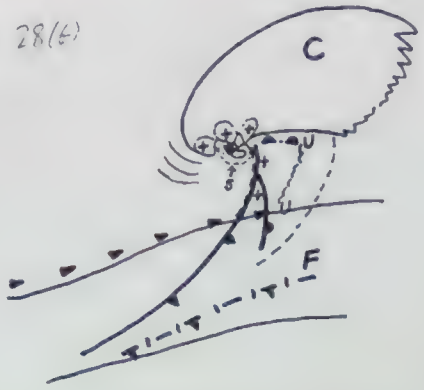
* Narrow band of heavy rain (along N coast of France) occurs beneath warm tops YY associated with the front at the forward edge of W1. Front indistinct at surface; most marked above 800mb

* Gap in rainfall over southern Britain persisted for many hours - due to deep layer of dry mid level air (partially obscured by cirrus XX) beneath jet axis

5.3.4.28 (a)



28(b)



43a

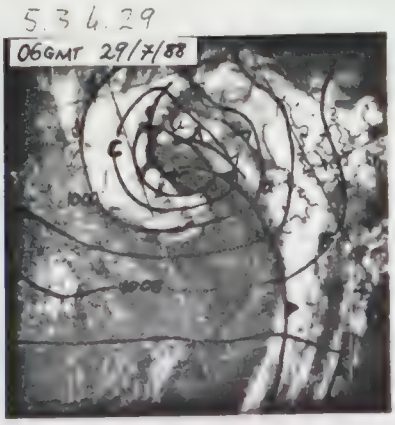
* C and F together conform to model illustrated in Fig. 5.3.4.28b (first described on p. 20)

* C and F are connected by low level cloud tops beneath dry wedge D - surface front lies towards the rear edge

* In this case the dominant warm front lies along inner edge of C

* Watch for possible development of "surge bands" (or deep convection) between C and F later in life cycle

5.3.4.29



* C has evolved into a hook around the depression centre which has almost reached its maximum depth (FIG. 5.3.4.29)

* Surge band of convection, UU, has now formed between C and F

* Convection also present along inner edge of C; embedded thunderstorms

The following NWP model forecast diagnostics valid at 12GMT 28/07/88 demonstrate how the onset of significant deepening in Type 4A events is dependent upon the correct representation of the small scale short wave / jet streak which forms between the axis of the main confluent trough and the surface low.

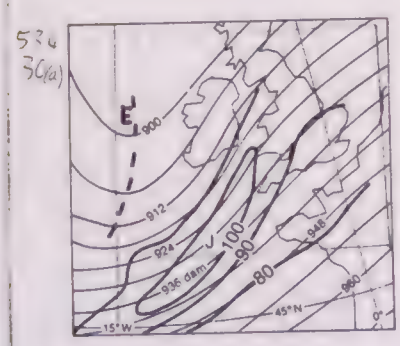
It is for this reason that NWP models often perform badly in Type 4A cyclogenesis, usually failing to deepen the low sufficiently. Therefore it is important to use the satellite imagery to look for early warning signs of cyclogenesis.

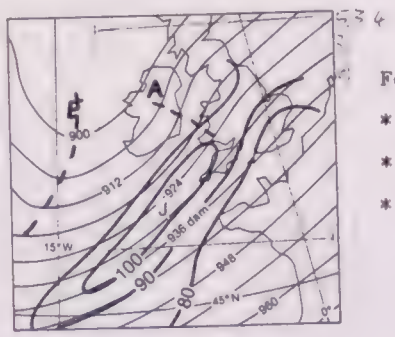
RUN 1 Poor run

Short wave at exit of jet J was not properly resolved

RUN 2 Better run

Short wave A was resolved at exit of J (because of extra aircraft reports which resolved J at earlier stage)



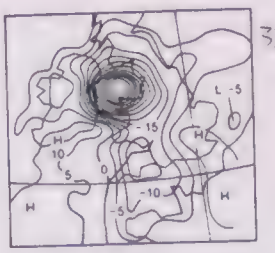


Forecasts of 300mb height (dam) and isotachs (kn)

* Confluent upper trough axis E

* Jet streak J

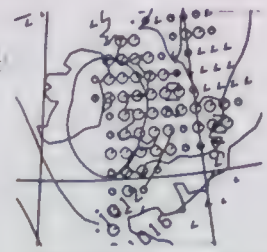
* Short wave A, not present in Run 1

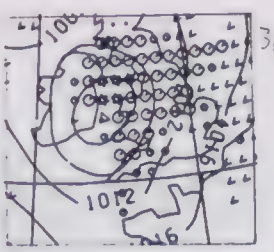


Forecasts of vertical motion (mb/h)

* In Run 2, PVA ahead of short wave A has helped to "focus" the ascending motion into a "bulls-eye", with values in excess of 55mb/h in vicinity of cloud area C

* In Run 1, in which A is absent, the upward motion is weaker and spread out over a larger area





Forecast sea-level pressure (mb) and rainfall rates

As a consequence of the vertical velocity distribution:

* There is a deeper low in Run 2

* Run 2 has correctly concentrated the rainfall over the Irish Sea with rates widely in excess of 4mm/h

* The area of forecast rainfall over SW England is smaller in Run 2 than Run 1, more closely resembling the gap in the rainfall distribution highlighted on the satellite / radar composite image

DYNAMIC RAIN
• <0·1 ⊕ >40 mmh⁻¹
○ 0·1-0·5
⊙ 0·5-40

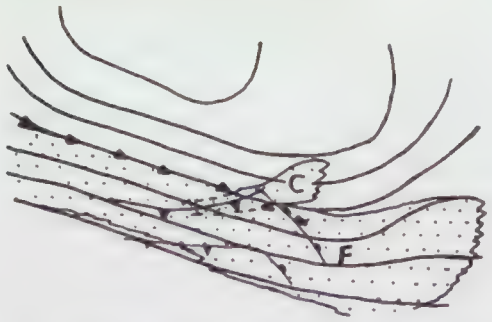
CONVECTIVE RAIN
v <0·5 ▽ >40 mmh⁻¹
V 0·5-40

43b

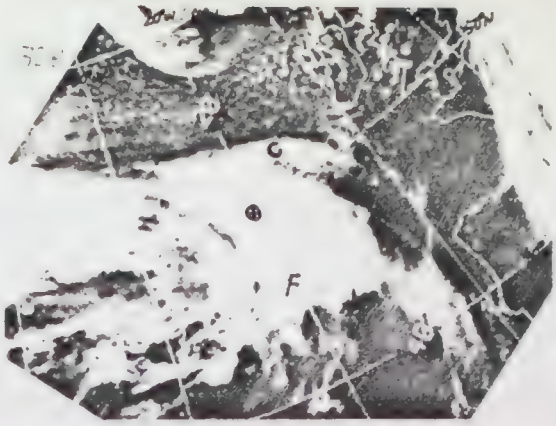
TYPE 4B FLAT ROUGH, DIFFLUENT FLOW

IDEALISED 300MB FLOW + CLOUD OUTLINE

5.3.4.32 (a)



INFRA-RED IMAGES



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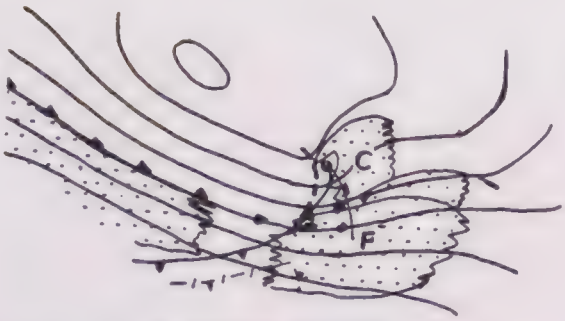
STAGE A — EARLY SIGNS OF POSSIBLE CYCLOGENESIS

- Mid-level layered* cloud C develops or emerges from beneath frontal cloudband F, often at an angle to edge of F
- Tops of C cool, area of C expands
- F may begin to dissipate upstream of C
- Poleward edge of F depicts jet axis. C lies within left exit of jet

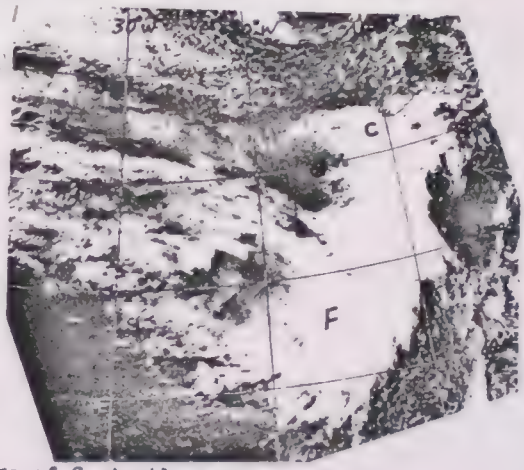
* C may consist of several areas of layered cloud (mini-leaves) or clumps of cumuliform cloud

Key
- • Ascent
- o Descent
- --- 850mb θ_w
- CA Cold advection
- WA Warm "
- PVA Positive vorticity advection
- NVA Negative " "

5.3.4.33(a)



33(b)



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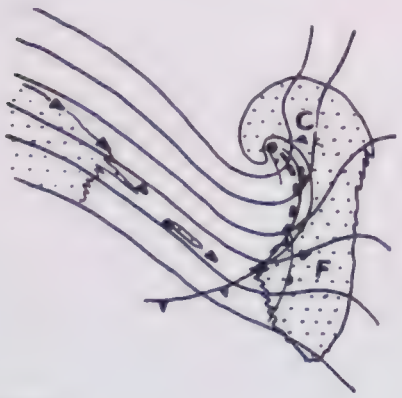
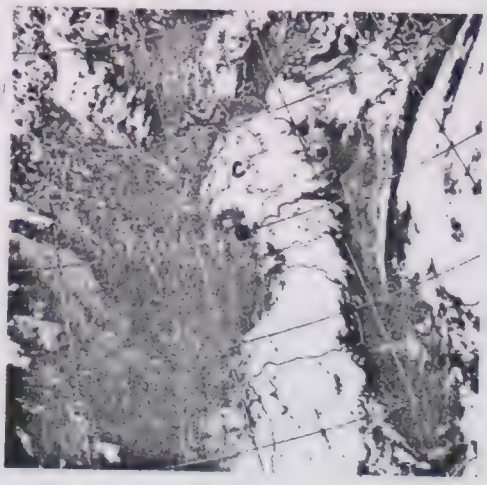
STAGE B — CYCLOGENESIS UNDERWAY

- C protrudes further from F
- If C is convective, cells develop at upwind edge of C. Anvils merge and are blown downwind
- Upwind edge of C moves forward of surface front as surge of dry air aloft penetrates between C and F
- Upper cloud within F dissipates rapidly behind the sharpening upper trough

5.3.4.34(a)



34(b)



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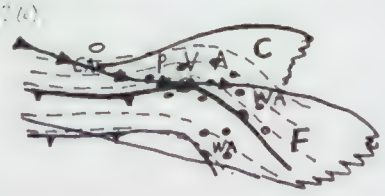
STAGE C — MATURING

- C becomes elongated within region of diffluent flow
- C virtually indistinguishable from F ahead of upper trough. To rear, F completely dispersed
- Arc-shaped region of dry cloudfree air aloft continues to surge forward. Surface front lies along rear edge of low cloud

Note: Although the main surface low has almost finished deepening, a new low may form near jet exit further south (See pages 52-53).

ADVECTION AND VERTICAL MOTION FIELDS

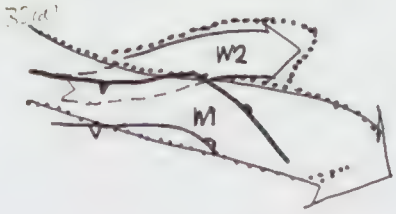


C Formed by new warm conveyor belt W2 of ascending air in region of PVA ahead of jet streak/ short-wave trough

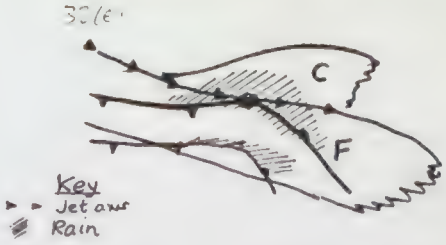
F Associated with higher level conveyor belt W1. F is densest and most persistent in region of WA next to C

Double frontal system often present. Deepening depression centre forms adjacent to C on more recent poleward front. Older equatorward front may still be present and possess a minor wave.

AIRFLOW MODEL



SURFACE ANALYSIS AND PRECIPITATION

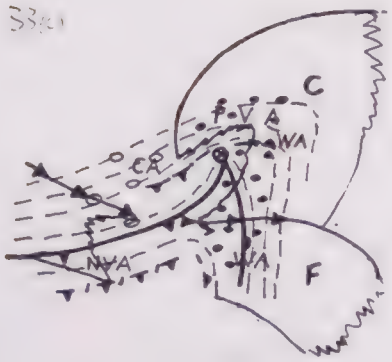


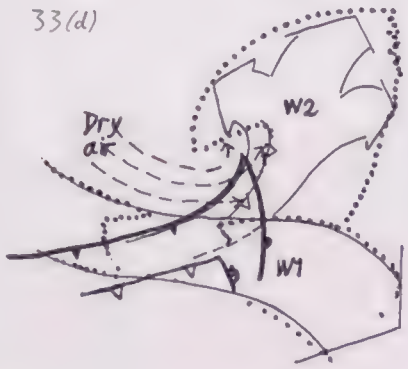
Precipitation is related to ascending WCBs

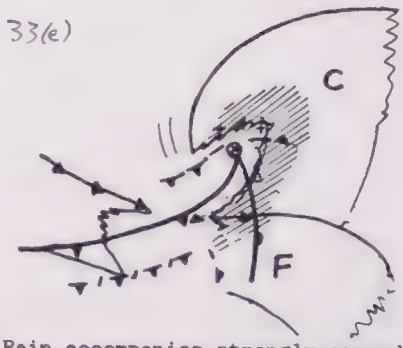
- Heavy rain within W2 on inside of C to north of poleward front
- Separate rain area may accompany equatorward front

Depression centre usually lies some 120-240nm in from inflection point X on poleward edge of C. (Apply rules 0-3 from section 5.1, p.6)

Well marked cold front







- C becomes more elongated as W2 emerges from beneath W1 and becomes cyclonically curved
- F dissipates to rear of C in region of subsidence because of CA behind low and NVA south of jet
- Dry air aloft overruns W2 north of jet causing air ahead of front to become potentially unstable. New upper cloud edge forms ahead of surface front
- Low-level thermal gradient often forms where W2 ascends over cold air (north of depression). New fronts can form here

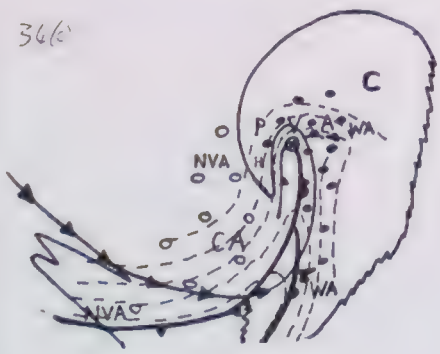
Rain accompanies strongly ascending air in W2

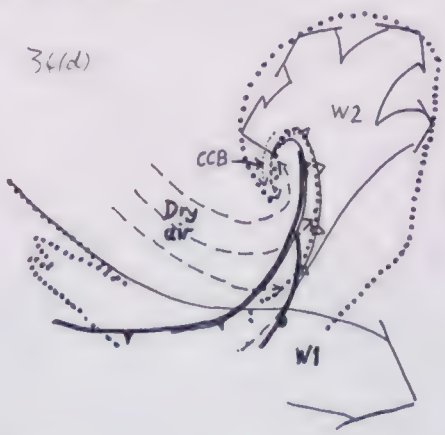
- Rain heaviest where mid-level convection present - around leading edge of dry surge, in particular to north of depression

Deepening depression beneath warm top on inside edge of C (Rule 4)

Mid-level convection cells often "fan out" from position of low centre (Rule 5)

After overrunning, cold front quickly becomes less well marked





- Hook of low cloud H forms behind depression in cold conveyor belt, CCB, originating on cold side of strong thermal gradient
- Warm air may seclude over low centre
- Elongated region of strong ascent along W2 due to PVA/WA ahead of amplifying upper trough - helps release PI
- Well marked split-front

- Area between H and upper cold front favoured for rapid convective development due to realease of potential instability

Secondary cold front is forward boundary of cold surface air

Streets of shallow convection S identify region of strong surface winds (>40kn) to rear of depression

EXAMPLE OF THE EVOLUTION OF A TYPE 4B CYCLOGENESIS

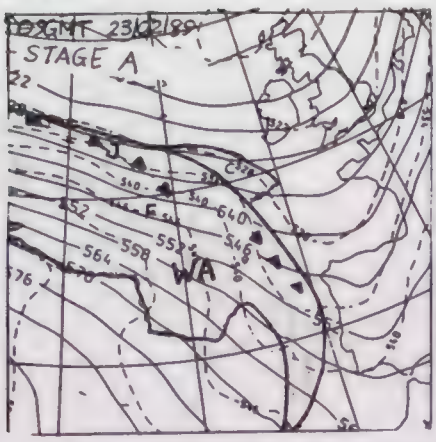
This sequence shows an example of the large scale evolution of a Type 4B cyclogenesis. Points worthy of note are as follows:

* C becomes conspicuously long during and after stage B. At the same time a well marked cloud free surge D develops between C and F, giving a hammer-head shape to the poleward end of C

* Two frontal systems are shown. The major thermal gradient is on the poleward system. The persistent region of cloud within F lies ahead of a minor wave on the equatorward system.

* The poleward edge of F is less well defined than usual.

5.3.4.35(a)



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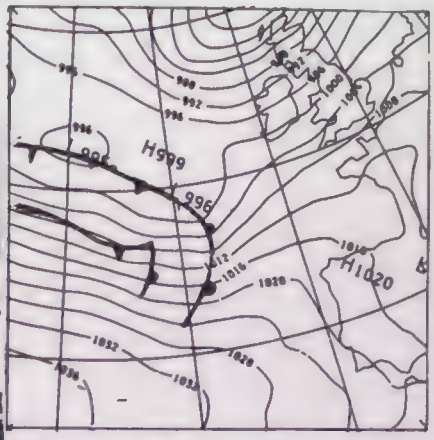
35(b)

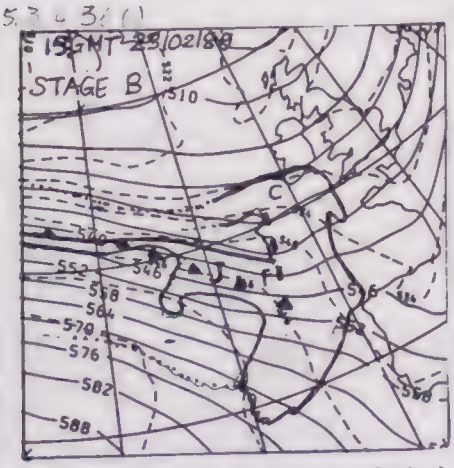
35(c)



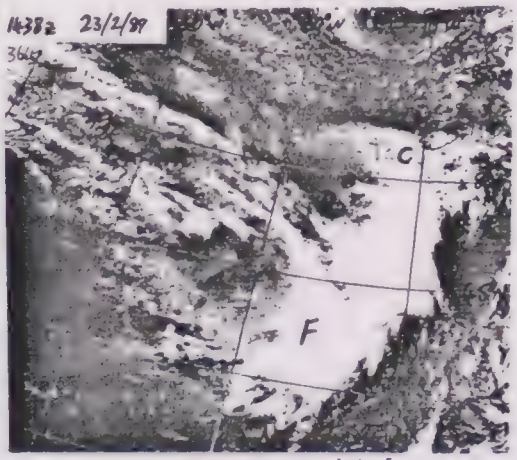
* C is situated ahead of a vorticity maximum V which lies on the left hand side of jet streak J. V is a good example of a vorticity "shear lobe", defined in Ch 3

* Two depressions are present initially. Since cloud area C is associated with the forward depression, it is likely that this will develop in preference to the rearward one

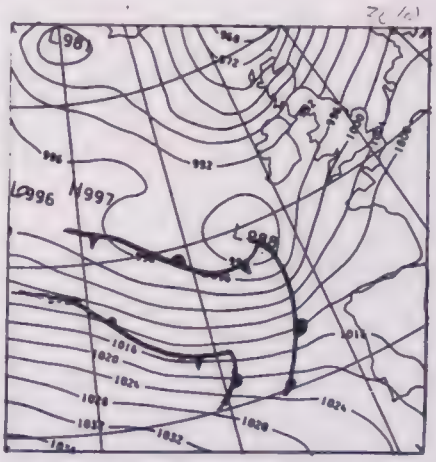
5.3.4.36(a)



1438z 23/2/89
36(b)



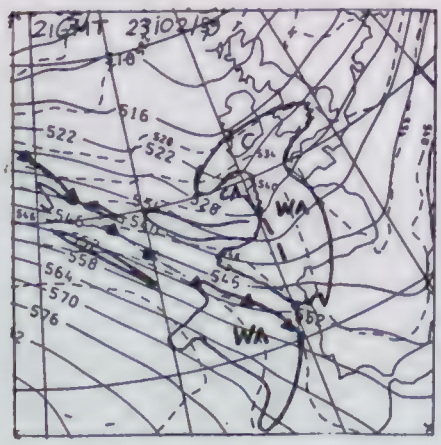
36(c)



* Short wave trough (bold, dashed line) becomes apparant as jet J "digs"

* Much of the upper and middle level cloud across the original baroclinic zone dissipates behind the short wave

5.3.4.37(a)



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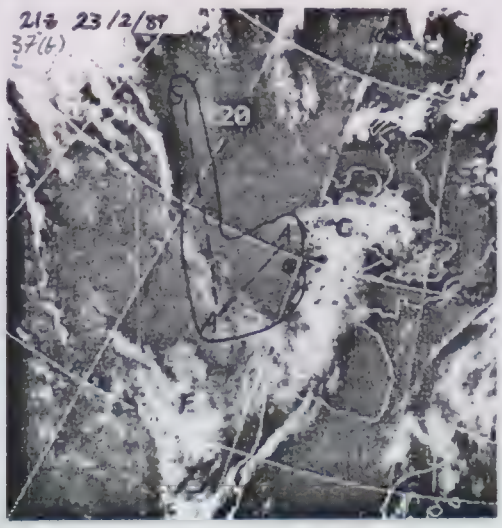
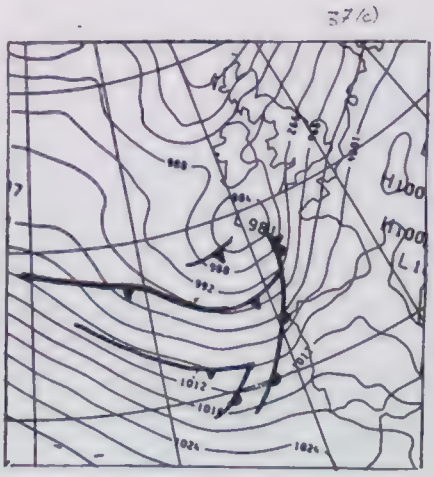
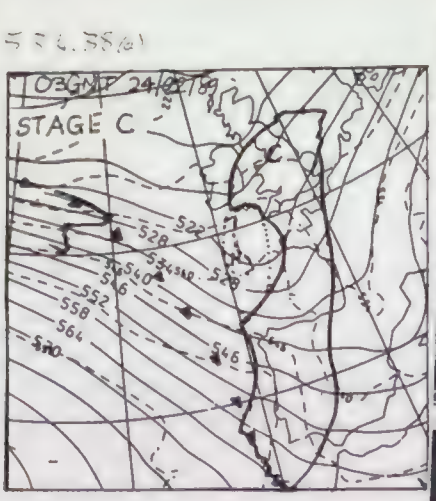
37(b)

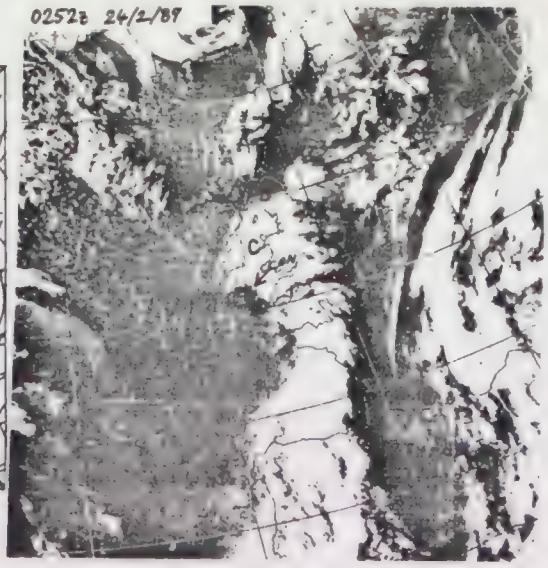


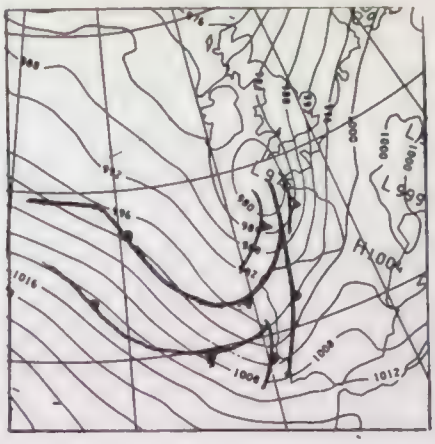
37(c)



* V expands and moves south east. It still possesses shear lobe AS, but has also formed an "advection lobe" AA in the sharpening short wave trough







* Now that the upper cloud across the baroclinic zone has disappeared, the jet axis is delineated by the transition from open to closed convection cells

* Once the dry wedge D has penetrated between C and F, the depression centre lies beneath warm cloud tops on inner edge of C. Deep convection cells labelled "CON" occur near the centre

* A split-front forms - see p~~xxx~~ 57 for mesoscale detail

DYNAMICAL PROCESSES (above)

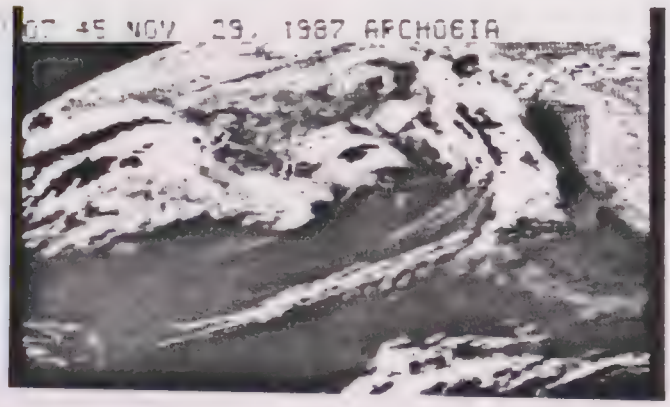
C - Situated in region of ascent (labelled ① - left fig.) due to PVA ahead of vorticity maximum V (top image previous page). As V expands and moves southeast, it is preceded by an increasingly elongated region of ascent (labelled ④ on right fig.), influencing the shape of the cloud pattern. In this region, upward motion due to PVA has also been reinforced by warm advection (WA).

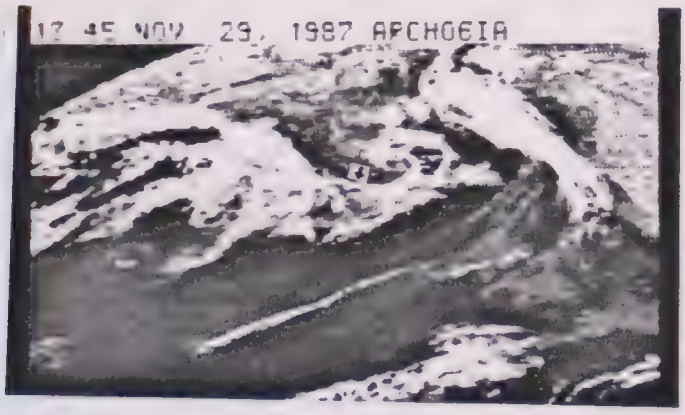
F - Most persistent south of C in regions of ascending motion identified by ② and ⑦, caused by a maximum of WA

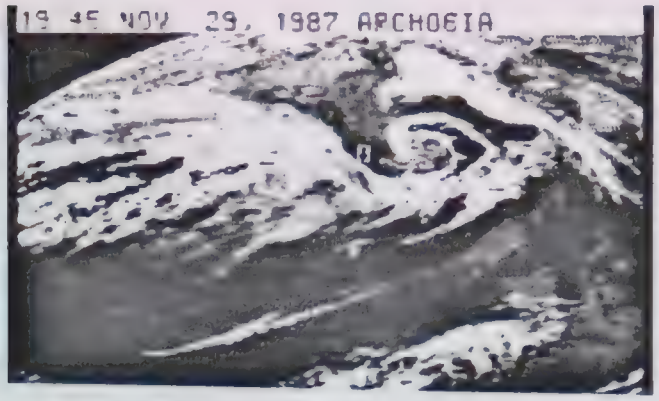
* Upper level cloud dissipation begins in region ③ (left fig.) where weak descent is present due to very slight CA.

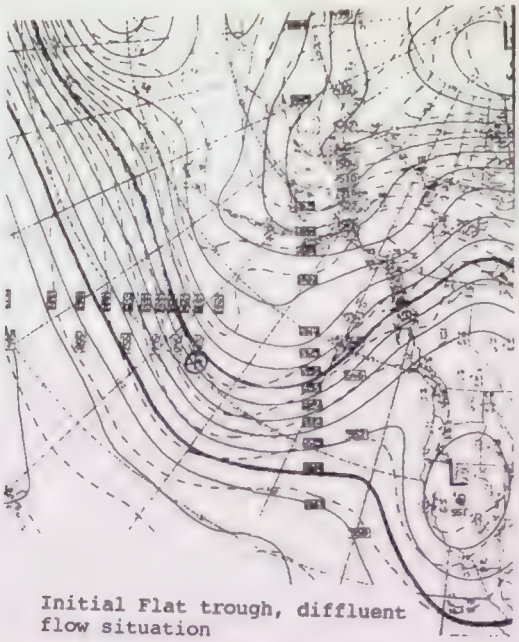
* By the later time (right fig.), considerable cloud dissipation has taken place across the baroclinic zone (region ⑥) as air subsides strongly due to NVA in the right exit of J.

* Cloud growth is suppressed behind C (region ⑤) due to combined CA and NVA









Initial Flat trough, diffluent flow situation

Figure 4

CMC 500 mb Height Analysis for 00Z on November 29, 1987

Cyclogenetic cloud signature:
- Two adjacent cloud areas C and F (top picture)
- Some evidence of a narrow dry wedge between C and F

As the upstream jet digs, a broadening arc-shaped region of dry cloud-free air enters the rear of the cloud signature

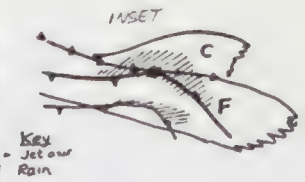
The cloud signature elongates during cyclogenesis and develops a strong circulation

The digging jet axis is shown up by the Cirrus edge (arrowed)

TYPE 4B EXAMPLES OF MESOSCALE WEATHER AND SURFACE ANALYSIS

Transition from Stage A to B

5.3.4.4C



04GMT 20/10/86 IR END OF STAGE A

Difference from archetype (inset)

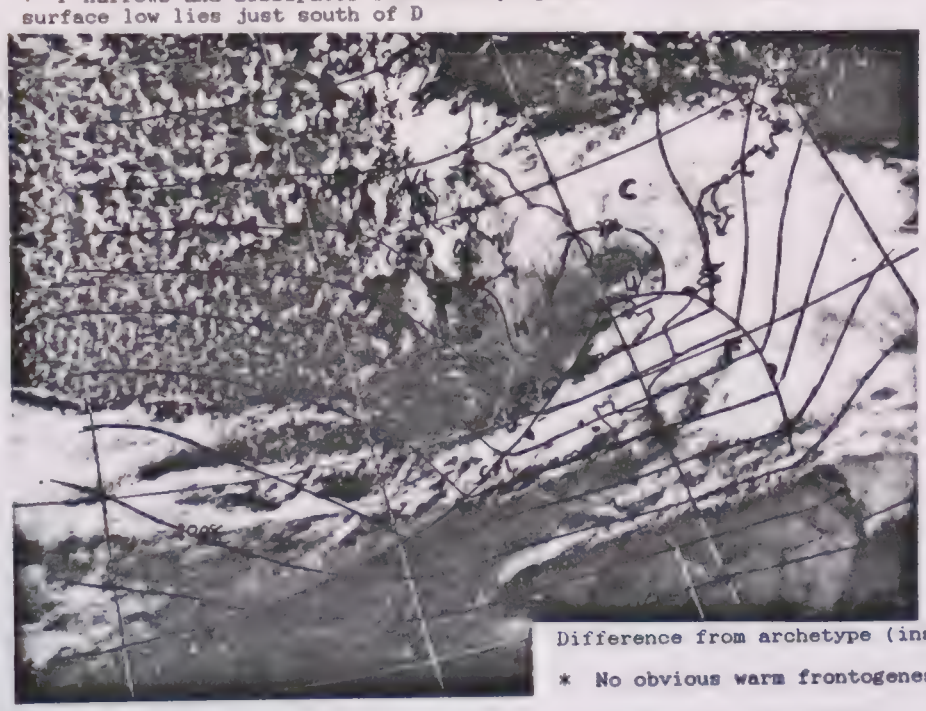
* C is a somewhat different shape
* C moves backward relative to F, not forward
* Only one frontal system is present

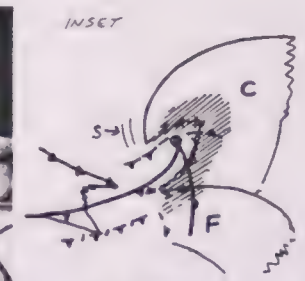
* Cloud canopy C has almost completely emerged from beneath frontal band F. In this case the northern boundary of C merges with a clump of deep convective cloud labelled "CON".

* A very narrow cloud free wedge D is beginning to separate warm tops along the inner edge of C and the northern edge of F

* F narrows and dissipates immediately upwind of C. An elongated surface low lies just south of D

5.3.4.4B





09GMT 20/10/86 IR TRANSITION TO STAGE B

Difference from archetype (inset)

* No obvious warm frontogenesis
* F more of an open wave

* Cloud area C has expanded and the tops have cooled

* A well marked dry slot D containing only warm (low) clouds now separates C and F. The depression centre lies beneath D

* C extends cyclonically to form a hook of low cloud H behind D. A secondary cold front CF2 forms along the inner edge of H marking the leading edge of cold air near the surface

* Upper cloud edge UU moves ahead of the surface cold front CF1 giving rise to a split-front over southern England with its characteristic rainfall pattern (see radar inset)

* Streamers of shallow convective cloud S indicating strong surface wind

Radar (covers boxed area on IR image)

* Rain beneath F, C and H. Rain-free beneath D

* Split front has just formed

Upper cold front at edge of upper cloud UU; rain ahead of it

Surface cold front CF1 behind UU; very narrow band of rain and a change of surface wind and temperature

New surface front CF2; much colder air behind.

EXAMPLE OF TYPE 4B (Stage A) 15GMT 21/1/88

5.3 4 42

The large area of cloud west of the British Isles initially lay forward of a flat confluent short-wave (Type 4A). However, with the upper flow rapidly becoming diffluent aloft (due to a veering upstream jet), the case is included as a good example of type 4B.

Features worthy of note are as follows:

* A layered cloud canopy C, which is particularly broad, lying north of cirrus shield F. (The northern edge of F is defined by jet cirrus plume JJ.)

* A possible (although poorly defined) dry wedge penetrating between C and F

The cloud signature has some similarities to a cloud head. Although the features are not as pronounced as in a "classical" cloud head (e.g. 30/01/88 p~~m~~), there is enough similarity to identify the system as a potential explosive deepener.

* Low centre lies adjacent to the rear portion of C

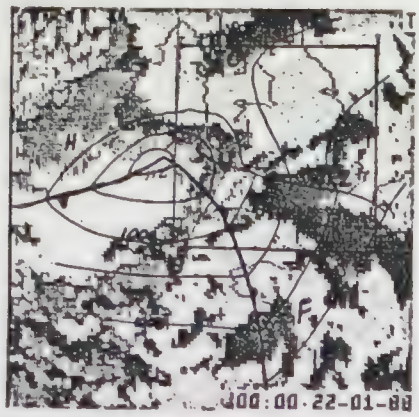
Differences from archetype (inset)

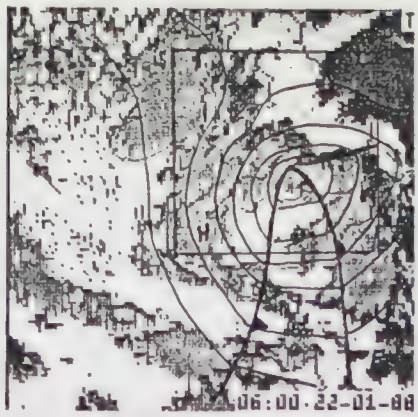
* No obvious equatorward frontal system beneath F

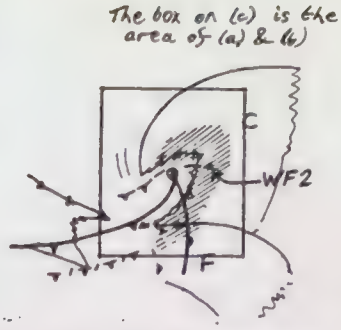
* The double warm front is not in quite the same configuration

TYPE 4B Evolution during Stage B

IR







* Upper cloud edge UU surges rapidly east southeast giving split cold front — UU is upper cold front

* Hook of low cloud H is carried south in strong northerly flow behind the depression

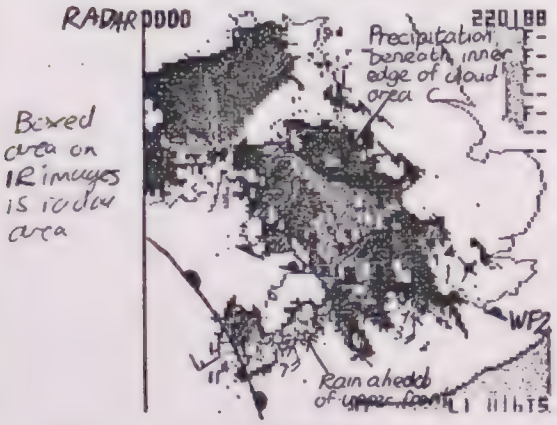
* Rapidly deepening depression centre located beneath warm cloud tops on the inside of C. Severe gales behind cold front at G

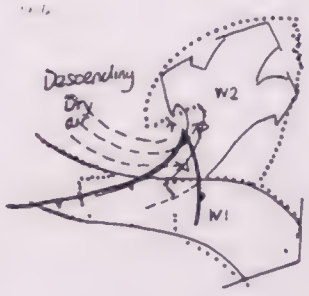
* The pressure trough accompanying the cold front becomes less well marked following overrunning

Schematic model of the depression at the stage depicted in adjacent IR images. Boxed area corresponds roughly to the area of the IR and WV images. In this example we have

* A well defined northern warm front, WF_2, north of which much of the precipitation is snow

* No evidence for a cold front inside hook H





Precipitation is more closely related to cloud edges and ascending conveyor belt W2 than to the surface fronts.

* Broad band of rain beneath strong horizontal gradient of cloud top temperature along inner edge of C

* Narrow rainband just ahead of upper cold front (UU on IR image)

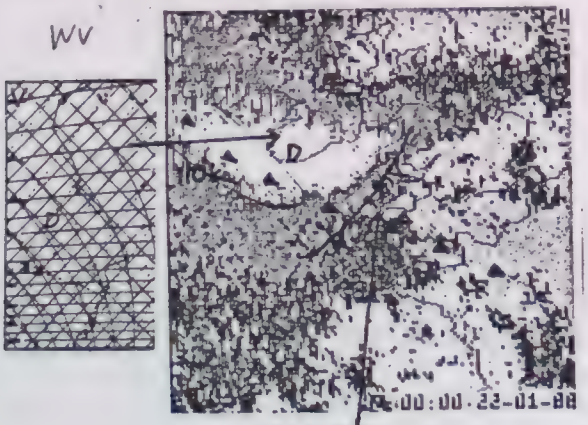
Radar images cover boxed area on above IR images

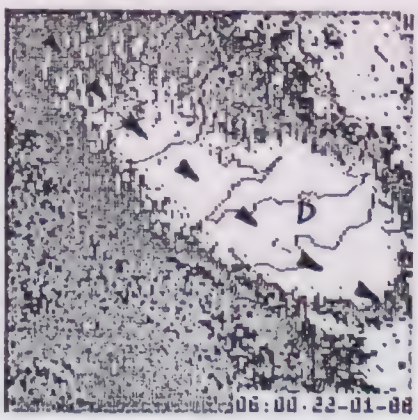
* Bands of rain along inside edge of C

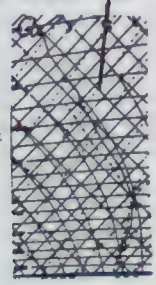
* Rain-free beneath dry air aloft

* small pockets of light rain beneath H

WV







Water vapour image shows very clearly the expanding region of dry air D moving rapidly forward, beneath and to the north of the jet - a common feature of rapid cyclogenesis

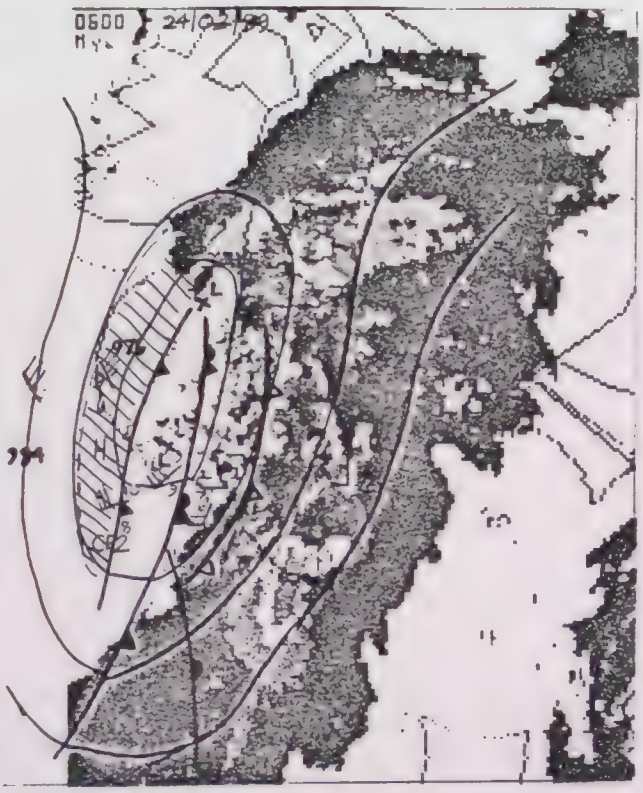
Deep dry layer D caused by descent of air from upper troposphere or lower stratosphere to below 600mb (shown on conceptual model)

In contrast, a deep layer of moist air lies ahead of the upper cold front

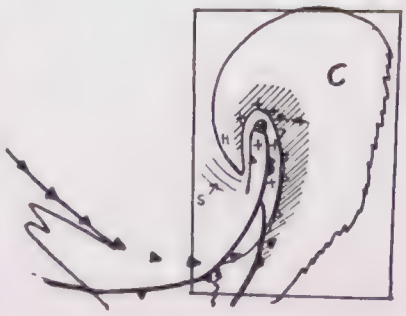
EXAMPLE OF TYPE 4B STAGE C

Combined satellite/radar image taken 3 hours after Fig. XX (See synoptic scale evolution) - boxed area.

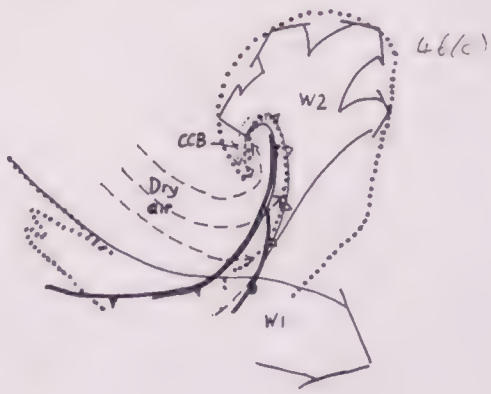
5.34.4(a)



4.6(b)



4.6(c)



Important features are as follows:

* Elongated area of middle and upper level cloud; rear edge marks the upper cold front (UCF)

* Hook H consists of low cloud only (shown schematically by hatching). This marks the cold conveyor belt (CCB)

Precipitation

* Broad area of rain ahead of UCF, associated with ascending warm conveyor belt W2

* Heavy showers between H and UCF; particularly widespread ahead of surface occlusion. This is where dry air aloft has overrun warm, moist low level giving rise to potential instability

* Narrow band of showers on CF2 at the forward edge of H

Surface analysis

* Elongated depression centre beneath warm cloud tops between H and UCF

* The occlusion in a good example of a split-front

* CF2 is a more recently developed front; marks leading edge of cold air in the strong northerly flow west of the depression

* No warm frontogenesis can be found - although the precipitation area extends east (region R) in the part of the system where frontogenesis is suggested by the schematic inset.

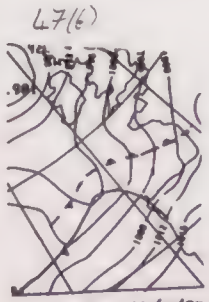
TYPE 4B EXAMPLE OF CONVECTIVE CLOUD / MINI LEAVES NORTH OF JET

In contrast to the relatively simple evolution on 24/02/89 (p~~**~~), a more complex cloud development sometimes occurs poleward of the jet during early stages of cyclogenesis. A series of convective cloud elements and "mini-leaves" can develop north of the jet as opposed to the emergence of a single, layered cloud mass, possibly due to a more convectively unstable environment.

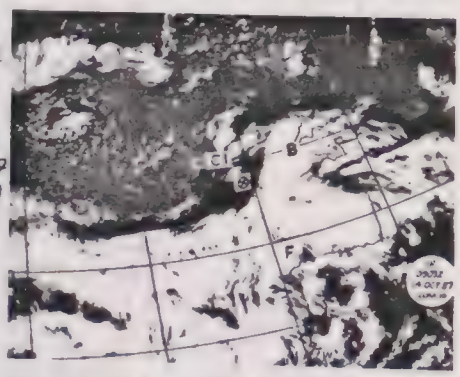
It can be difficult to predict whereabouts the dominant low pressure centre will form, within the often quite large cloud signature. (Such information is important if for example, cyclogenesis is taking place over an area for which detailed local forecasts of wind are required.) However, satellite imagery offers some clues which are illustrated in the following examples. In this type of upper air pattern, NWP models have considerable difficulty identifying which of several centres will be dominant, and usually significantly underestimate the overall deepening.

Important features on the imagery are as follows:

0504Z 14/10/87 Nom 9



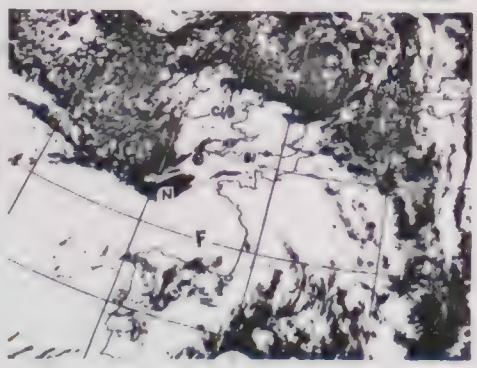
* Early warning of possible cyclogenesis; simultaneous growth of mini-leaf B and deep convective cloud elements C1 in left exit of jet to poleward side of F



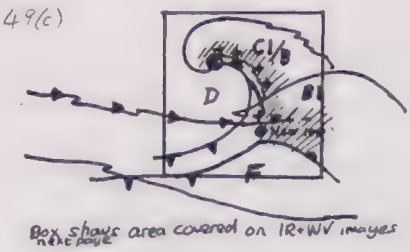
0903Z 14/10/87 Nom 10

* Convection C1 grows rapidly - suggests that dominant cyclogenesis will occur in conjunction with C1 rather than B

* Cirrus outflow from C1 expands and merges with B

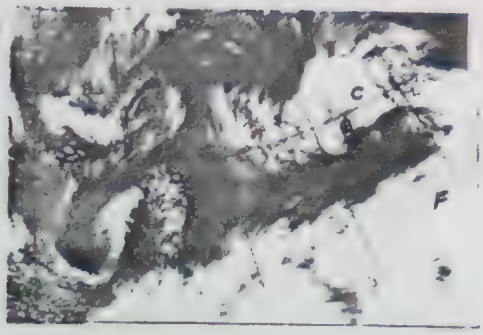


1458Z Nom 9 14/10/87

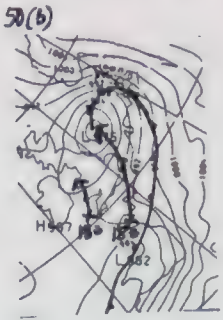


* New leaf B1 appears north of F, along with small dry "notch" N; signals possible new cyclogenesis at equatorial edge of B1 as jet "digs"

* Cloud canopy C/A becomes elongated



0502Z 15/10/87 Nom 9



Surface analysis

* Double frontal structure

* The depression centre is situated at rear edge of cloud extension north of jet

* The new low can be thought of as "triple point" cyclogenesis in cases where the data coverage cannot resolve the double front

The following images highlight the important aspects of the mesoscale weather distribution relevant to local forecasting, as the system moves over a data-rich area.

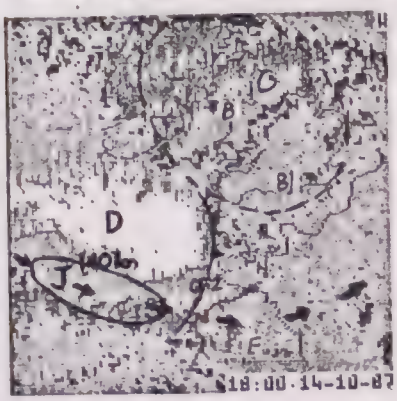
WV images

* Expanding region of dry air D beneath and to north of jet streak J moves east immediately behind deepening depression

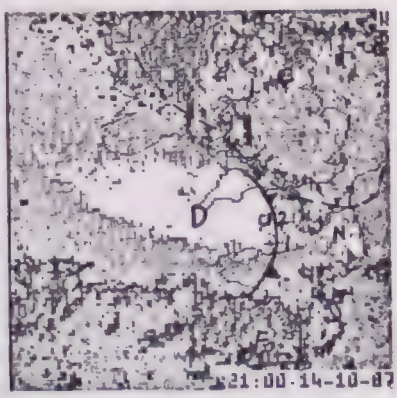
* Small dry notch N at forward limit of D; appears to provide early warning of new low L forming as J interacts with inner frontal zone

* Dry air overruns cold front CF2; front becomes poorly defined (see surface analysis)

5.3.4.51(a)



51(b)



IR images

* New convective cloud growth (arrowed) occurs at rear edge of cloud extension

* Depression centre lies at rear edge of cloud extension, beneath warm cloud tops - deep convective cells concentrated near low centre

* Hook of low cloud H moves equatorward in strengthening northerly flow west of depression centre

* First leaf B and new leaf B1 identified by regions of cold cloud tops

5.3.4.52(a)

52(b)

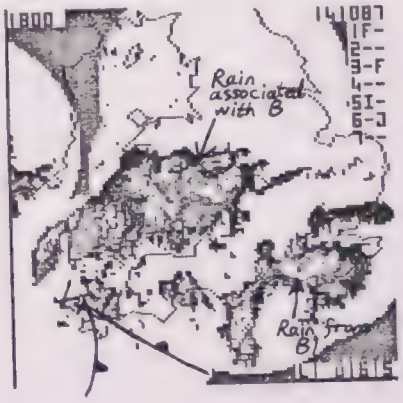
Radar images (Boxed area on IR figs)

* Precipitation found along rear portion of cloud extension C1/B/B1 (on forward side of dry zone D) as suggested in the schematic figure (repeated below)

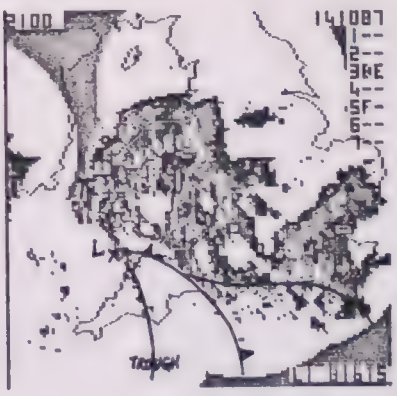
* Many embedded convective cells; thunderstorms probable

* Organised rain areas associated with cloud areas B/B1

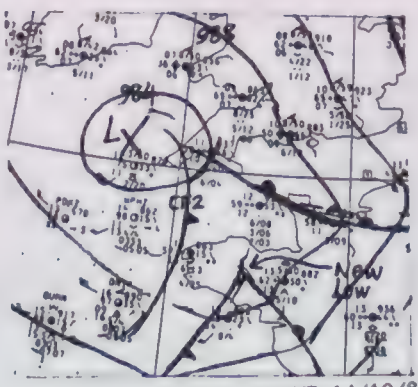
5.3.4.53(a)



53(b)

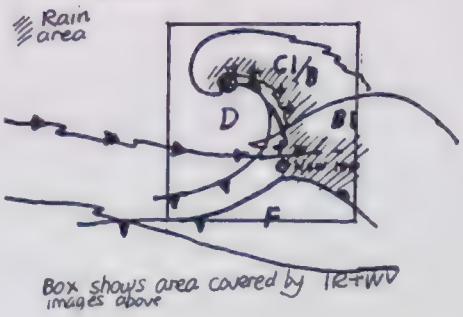


5.3.4.52(a)



Surface analysis 18GMT 14/10/87

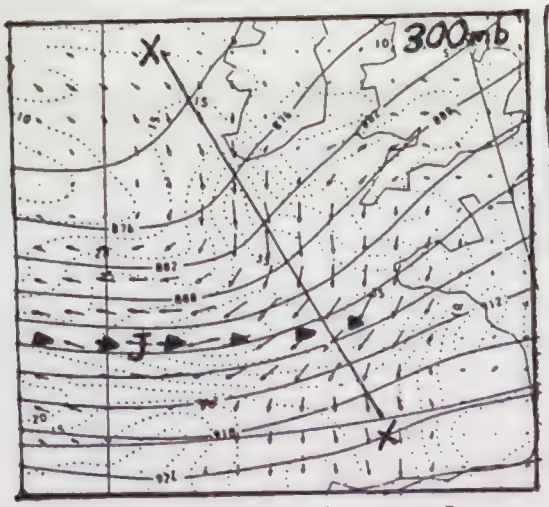
54(b)

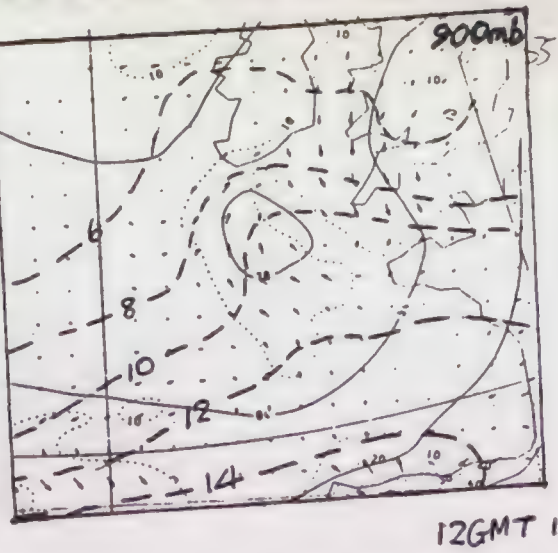


Box shows area covered by IR+WV images above

TYPE 4B EFFECT OF THE CROSS-CIRCULATION AT THE JET EXIT

53.4.55 (a)





55(b)

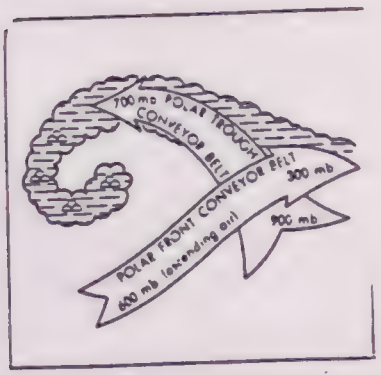
--- θ_w (°C)

12GMT 14/10/87

→ Ageostrophic wind component

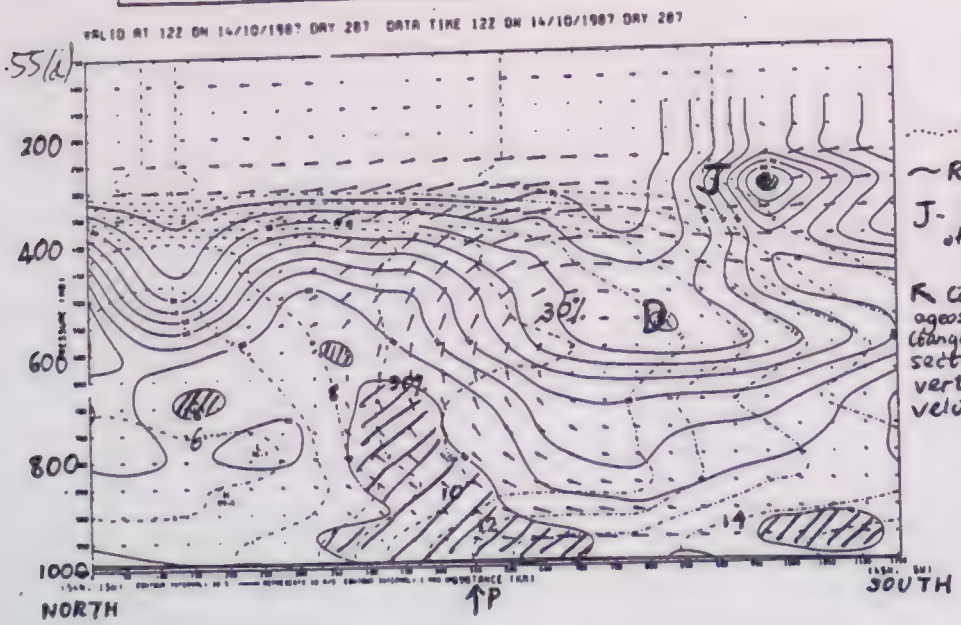
Convective cloud elements form at the left exit of the jet J due to the indirect ageostrophic circulation. At upper levels in the left exit region (Fig.55(a)), air moves up the geopotential gradient, whilst at low-levels (Fig.55(b)), the resulting counter-current extrudes a narrow tongue of air of high θ_w from beneath J.

55(c)

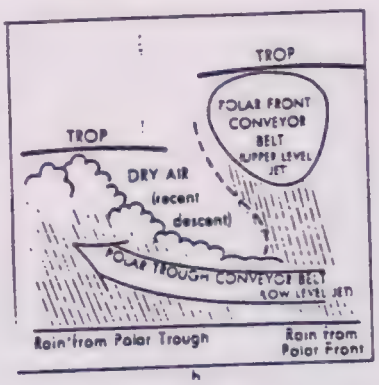


The low-level flow takes the form of a "polar trough" conveyor belt" which emerges from beneath the jet axis (and its associated polar front conveyor belt). With the introduction of high θ_w at low levels, the region north of the jet becomes potentially unstable and the instability is released in the form of deep convection cells due to ascending motion at the left exit.

55(d)



55(e)



Left hand figure. The indirect circulation at the jet exit is illustrated in this NWP model cross-section along line XX (Fig. (a)). The lower and upper branches of the circulation are coupled by a deep layer of strong ascending motion and high relative humidity (shaded), at P, corresponding to cloud area C. The low level branch transports air of high θ_w (rearward) from beneath the jet. Potential instability evident, for example between 950 and 650mb at P is released from the top of this layer. A tongue of mid and upper level dry air D lies north of the jet in the weakly descending part of the circulation.

Right hand figure. This summarises the main processes illustrated in the NWP model section. It is effectively a vertical section along the polar trough of Fig. (c).

EXAMPLE OF TYPE 4B SPOT THE STORM!!! 18/12/86

In this example a new jet maximum lay immediately upstream of cloud areas B/C1, along the poleward edge of frontal cloudband F. The example illustrates a technique for pinpointing the favoured location for cyclogenesis (and therefore locations most at risk from very strong winds) in a complex cloud signature.

Fig.5b(a) 0911GMT 18/12/86 The cloud signature over the British Isles appears cyclogenetic (as described in section 5.2 - precursors). However, the important question is - where will cyclogenesis take place? Two possibilities are as follows:

(i) A deepening depression may form immediately behind convective band C1 (where at present only a trough exists)

(ii) Cyclogenesis may occur adjacent to new leaf B, just beginning to form adjacent to F.

Fig.5b(b) 1512GMT 18/12/86 On this image, the superimposed pressure pattern reveals two incipient low centres labelled Y and Z. Up to this stage, pressure tendencies were -6mb/3h or more ahead of both centres. In order to answer questions (i) and (ii) above, important clues are as follows:

(1) Cloud area B, adjacent to Low Z had grown considerably indicating strong upward motion.

(2) The false colour Meteosat image (Fig.5b(c)) shows a progression from warm, low cloud tops on the inner edge of B to cold, high tops further north suggesting that the concentrated ascending motion in B is predominantly slantwise.

(3) In contrast, cloud area C1, associated with Low Y, has not grown during this time.

The conclusion from (1) and (2) is that Low Z should be the focus for new cyclonic development in preference to Low Y. Low Z did, in fact, deepen 20mb in the 9h following the time of Fig. (b) and went on to cause storm-force winds over the north coast of the Netherlands several hours afterwards.

Fig.5b(d) illustrates how the cloud structure relates to the rainfall distribution. The main features are:

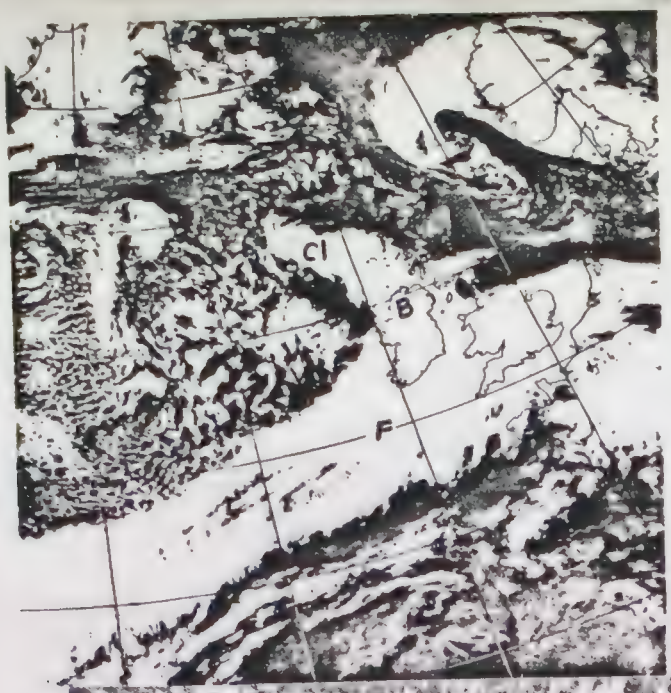
* A compact region of moderate and heavy rain beneath and adjacent to cloud area B

* A narrow band of convective rain along the northern cold front F2, at the extreme range of radar coverage

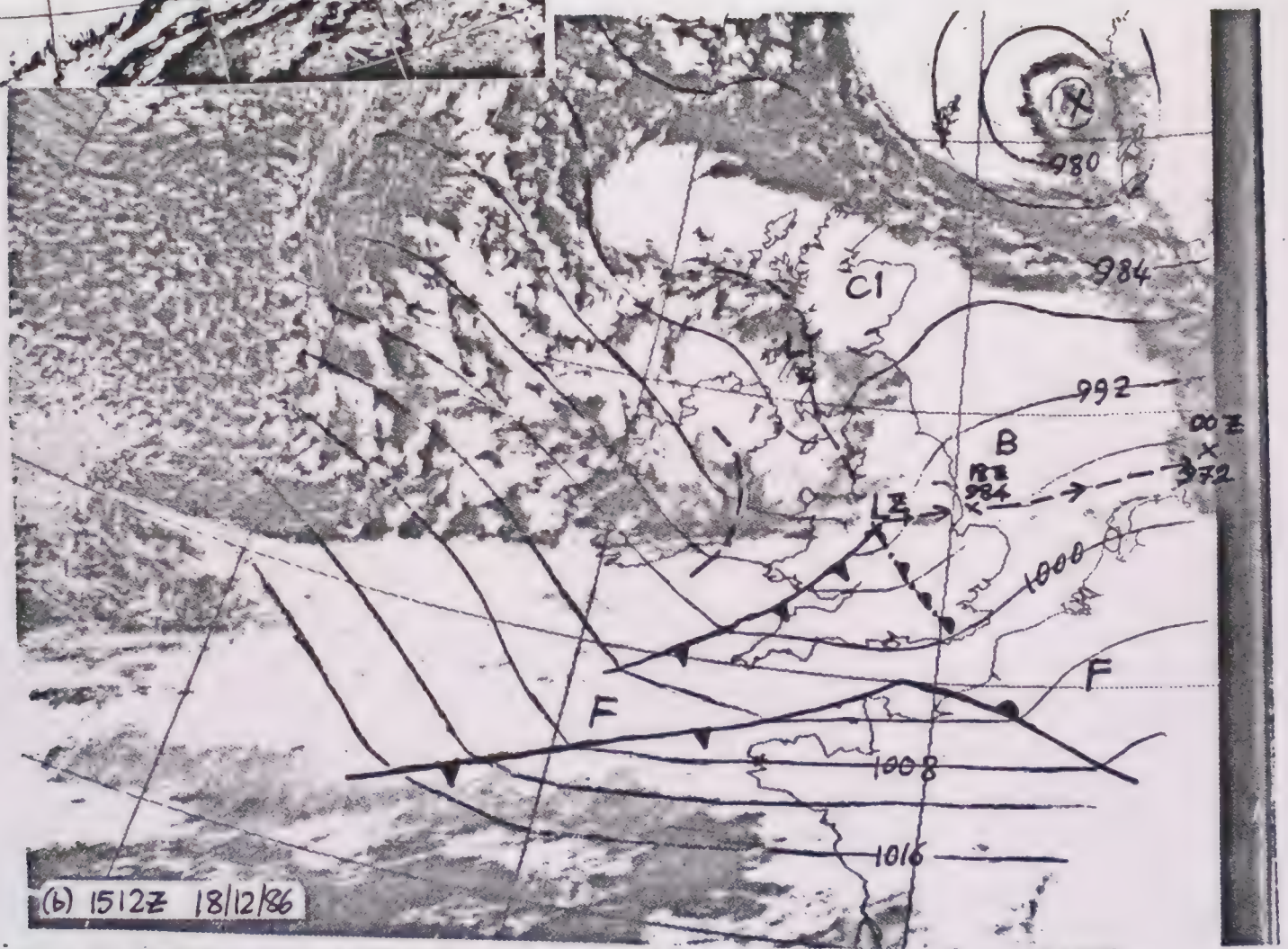
* A separate area of light and moderate rain associated with the inner frontal system F1.

5.3.4.56
(a)

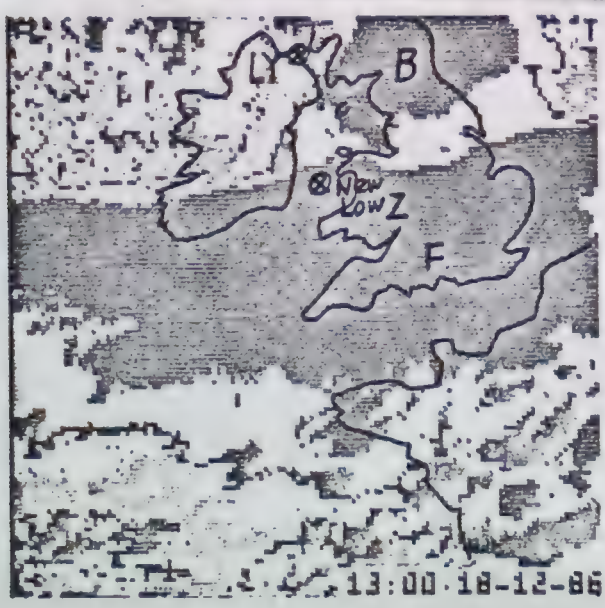
0911GMT 18/12/88 IR

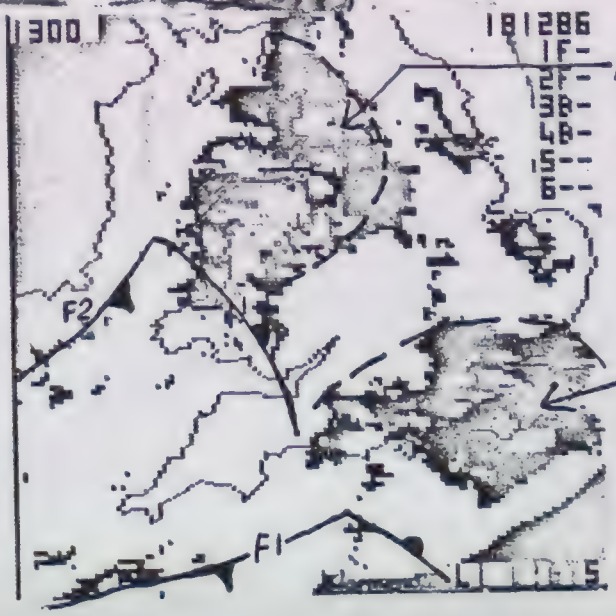


56(b)



56(c)





Rain from leaf B 56(d)

Rain from inner fronts

5.4 Mature occluded depressions

Synoptic scale

The sequence of schematics in Fig. 5.4.1 shows cloud associated with an occluded depression as it fills. The sequence usually covers a few days but there will of course be variations if development areas move into the region.

During rapid deepening of a depression, the cloud band of the occlusion (O on Figs 5.4.1(a), (b)) quickly wraps around the depression centre (which will be almost collocated with the upper-level vortex) several times. Dry air, often very unstable, is entrained into the circulation, also forming a spiral. From this time forward, the circulation gradually decays, the central pressure rises and the clouds around the centre of the vortex become less organized.

The spiral of cloud begins to break up into multiple bands with alternating clear and cloudy 'lanes' (Fig. 5.4.1(c)). The main frontal cloud band moves to the periphery of the cyclonic circulation, leaving the remnants of the occlusion cloud band to define the weather around the centre of the filling system.

Later on (Fig. 5.4.1(d)), the outer limit of cloudiness associated with the old occluded cloud band marks the boundary of a large envelope of low-level and mid-level cloud tops. This is effectively a moist layer covering a large area, typically about 1000 km in diameter, with extensive Cu, Sc and St; this area is distinct from the clearer skies (often with open cell convection) around the periphery. Most of the precipitation is concentrated into narrow bands of convection which break through the top of the moist layer. For example, a succession of comma-shaped cloud features can become detached from the inner part of the spiral associated with the occlusion. Such commas are often accompanied by small surface circulations.

Fig. 5.4.1(e) shows the final stage, which is presented in more detail in Fig. 5.4.2. The pattern is similar to that shown in Fig. 5.4.1(d). The vortex moves only slowly while the features within its circulation move cyclonically around it. Small comma clouds often form from the remains of the old occlusion cloud band, some of which (e.g. C on Fig. 5.4.1(e)) may protrude outside the main cloud envelope. The cloud may dissipate in the equatorward and western quadrant, where there is often larger-scale subsidence within the filling system.

Mesoscale

The cloud patterns

Organized areas of precipitation rotate around the main vortex centre and may persist for up to a day. They act as a focus for shower activity and may be present at any time of the year. Between them, and outside the moist area, the distribution of showers may be influenced by topography or the showers may be suppressed.

There are often larger, more organized, areas of convective cloud such as the following.

- Commas may form directly from the cloud band of an old occlusion associated with a short-wave trough and weak WA.
- Bands often form ahead of minor short-wave upper troughs moving around the vortex (e.g. A and B in Fig. 5.4.1(d), B in Fig. 5.4.2).
- An organized band of precipitation (with embedded convection) will often lie along the rear edge of the larger commas.
- Thunderstorms and perhaps mesoscale convective systems may develop, especially in the summer half-year over land.
- The development of convective cloud (usually in the form of a comma) is strongly favoured immediately ahead of the vortex centre, at K in Fig. 5.4.2. Convective precipitation often persists near the vortex centre (i.e. within about 200 km) even without assistance from surface heating (e.g. well inland overnight and during the autumn or winter). Thunderstorms are particularly likely in this region by day inland during spring and summer.

- Areas of convective cloud over the sea in spring and summer indicate regions of considerable instability, with potential for thunderstorm development on arrival over warmer land by day. Any significant cloud breaks within the moist zone can readily be filled with new convective cloud when there is significant surface heating.

The upper flow is often slack and diffluent poleward of the vortex. Cloud bands (e.g. G in Fig. 5.4.2) often become slow moving relative to the vortex in this region, merging with the remains of the old occlusion band. To the rear of the vortex (within the region marked by the dashed line on Fig. 5.4.2), cloud tops eventually begin to warm. This warming often gives a preliminary indication of air-mass stabilization due to subsidence, with a corresponding decrease in shower activity.

Predicting the movement of convective bands

- If the convective band lies ahead of a short-wave trough that has been resolved in an NWP model e.g. at 500 hPa, then the diagnostics may be used to predict its subsequent movement.
- The movement of cloud and precipitation areas, derived from a series of satellite and radar images, may be forecast over a period of hours by extrapolation.
- The precipitation areas move approximately at the velocity of the wind near the mid-level of the cloud.

For examples of satellite and radar signatures associated with mature depressions, see *Images in weather forecasting* (Bader *et al.*, 1994), Section 5.4.3.

5.4.1

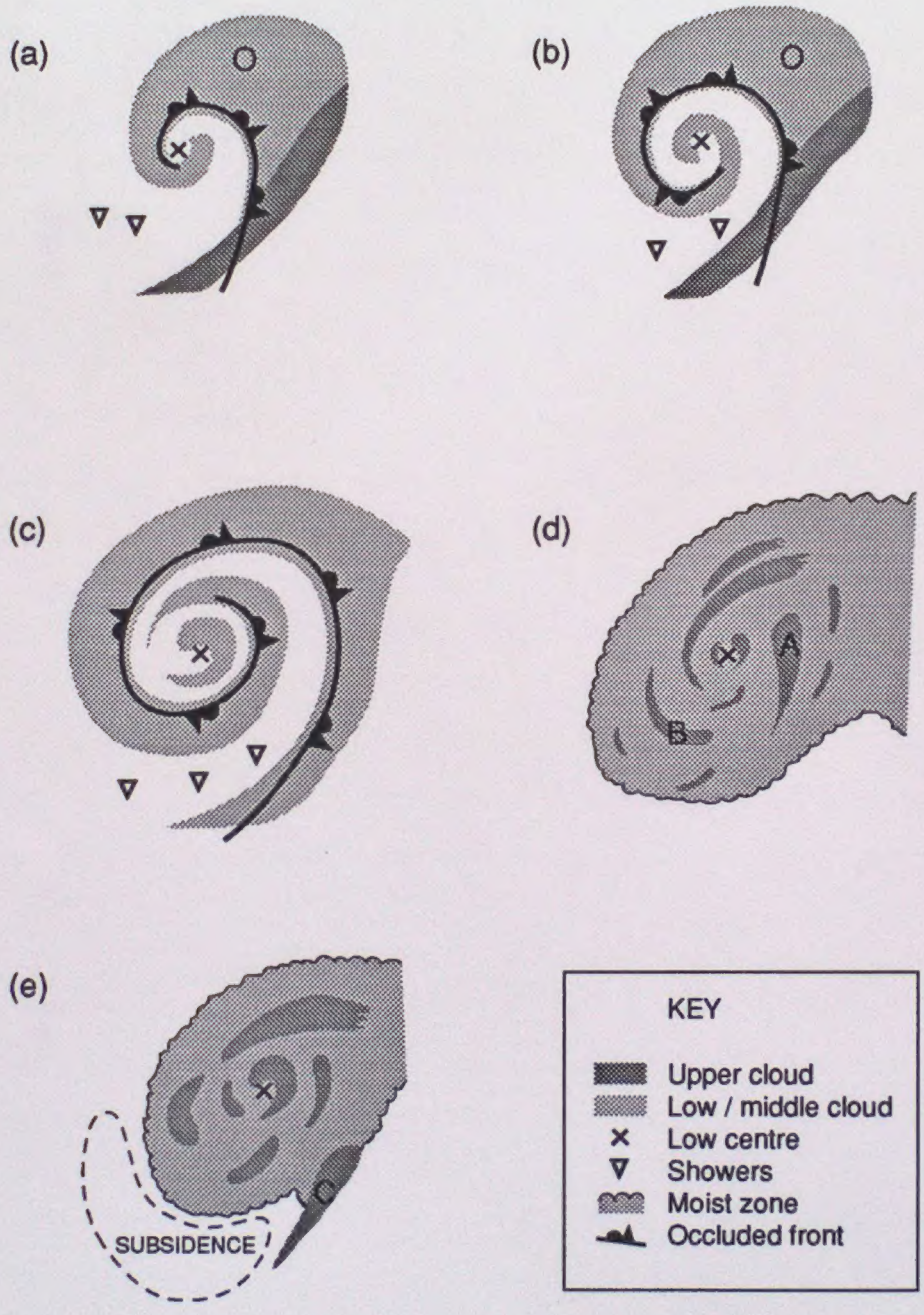
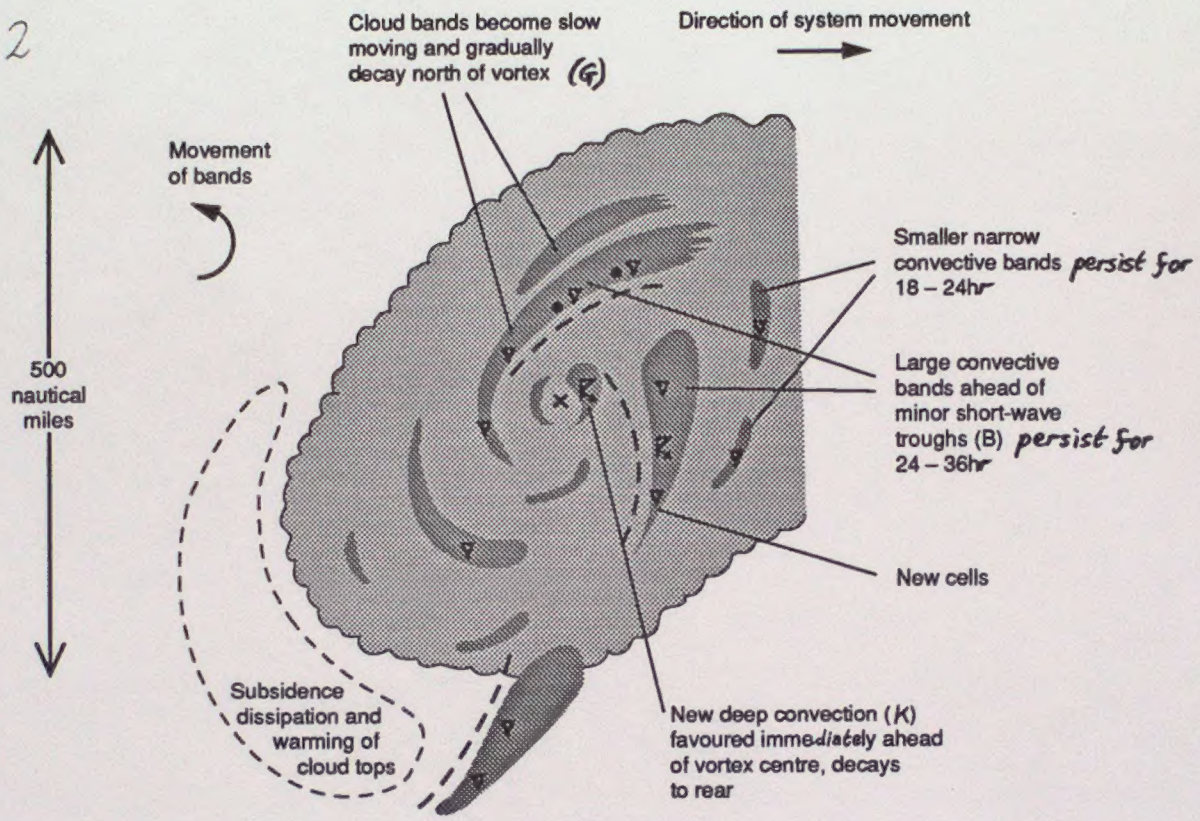


Fig. 5.4.1. Schematic life-cycle of a mature depression. (a) The depression has achieved its lowest central pressure. (b) The cloud band spirals around the centre. (c) The cloud breaks into multiple bands. (d) Narrow bands of convection show above the moist lower layers. (e) Subsidence (often marked in the area indicated) leads to stabilization. O is cloud associated with the occlusion; A, B and C are cloud areas associated with convergence zones or short-wave troughs moving around the main vortex.

5.4.2



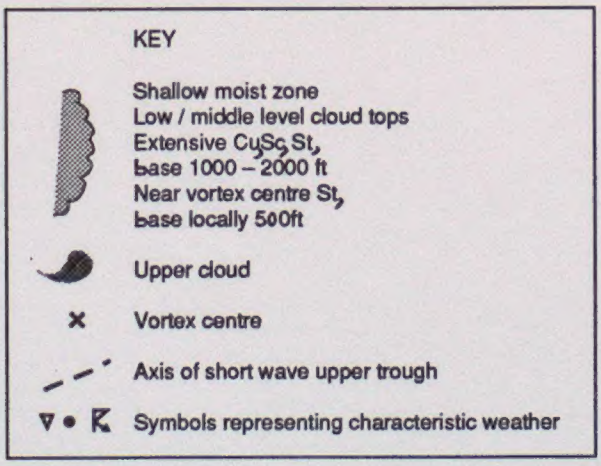


Fig. 5.4.2. Schematic of cloud areas around a mature depression, corresponding to Fig. 5.4.1(e). For labels, see text.

5.5 Depressions that are unlikely to deepen significantly or that do not complete their development cycle

Satellite imagery clues

The following changes to an initially well defined cyclogenetic cloud signature with a well marked poleward edge (see e.g. Section 5.1, pp. 2 and 5) indicate that the accompanying depression is unlikely to deepen much further:

- becoming ragged and less well defined;
- shrinking;
- becoming generally less dense, with holes developing;
- sustained warming of the cloud tops.

Upper air pattern

The differences between upper air patterns that favour rapid deepening and those that do not are often very subtle and difficult to analyse using available upper air reports, hence the importance of looking for clues in the imagery. However, the following features characterise broad-scale flow patterns accompanying depressions that have their life-cycle terminated prematurely or do not deepen any further:

- the depression and its accompanying cloud signature move away from the upper trough that triggered the initial development;
- the depression moves beneath anticyclonically curved flow aloft;
- the upper trough relaxes, with only relatively weak flow around the base.

Note that in the above scenarios, although very strong winds will persist on the equatorward flank of the depression, it is unlikely that the new region of particularly strong winds referred to on p. 29 will form to the rear of the depression.

For examples of non-deepening depressions, see *Images in weather forecasting* (Bader *et al.*, 1994), Section 5.5.

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